

Final Technical Report
(According to NASA Handbook NHB 5800.1C)

A LOW COST SIMULATION SYSTEM
TO DEMONSTRATE
PILOT INDUCED OSCILLATION PHENOMENON

043545

512

Syed Firasat Ali
Principal Investigator
Aerospace Science Engineering Department
Tuskegee University, Tuskegee, AL 36088

NASA Dryden Flight Research Center
Research Grant No. NAG 2-4006

April 1, 1994 to January 15, 1997

ABSTRACT

A flight simulation system with graphics and software on Silicon Graphics computer workstations has been installed in the Flight Vehicle Design Laboratory at Tuskegee University. The system has F-15E flight simulation software from NASA Dryden which uses the graphics of SGI flight simulation demos. On the system, thus installed, a study of pilot induced oscillations is planned for future work. Preliminary research is conducted by obtaining two sets of straight level flights with pilot in the loop. In one set of flights no additional delay is used between the stick input and the appearance of airplane response on the computer monitor. In another set of flights, a 500 ms additional delay is used. The flight data is analyzed to find cross correlations between deflections of control surfaces and response of the airplane. The pilot dynamics features depicted from cross correlations of straight level flights are discussed in this report. The correlations presented here will serve as reference material for the corresponding correlations in a future study of pitch attitude tracking tasks involving pilot induced oscillations.

ACKNOWLEDGMENTS

The research project covered by this report was sponsored by the NASA Dryden Flight Research Center under grant number NAG2-4006. Mr. Larry Shilling's support and encouragement and Mr. Ken Norlin's expertise on simulation software were vital to the completion of this work.

Dr. Amnon Katz from the University of Alabama and Dr. Vascar G. Harris from Tuskegee University, who are both pilots and aerospace engineering professors, contributed greatly by providing their invaluable support and insights on such issues as experimental design, statistical data processing, and most importantly, relating the data to a pilot's performance.

Jason Williams, an aerospace engineering student at Tuskegee University, enthusiastically participated in all aspects of the research project including alterations in the software, system trouble shooting, and developing C++ codes to aid in calculating and graphing of the cross correlations. Together with Yusef Johnson, a fellow aerospace engineering student, Jason coordinated the conduct of the test flights performed by the volunteer pilots and even participated as one of the simulator pilots in the study. It should also be noted that Yusef demonstrated keen interest in obtaining and understanding the cross correlations.

Despite their professional commitments, Dr. Larry Koons, Mr. Nathaniel Glover, and Glen Morean devoted their valuable time as volunteer pilots to conduct all of the required test flights.

Special appreciation is expressed to Dr. C. L. Chen, Abraham George, and Ernest Kashiri who are faculty and staff members of Tuskegee University for providing substantial advice on software related issues.

Ronald Jones and Dennis Ezell, Tuskegee University aerospace engineering students, deserve special recognition for their efforts in helping to initiate flight simulation research at Tuskegee University. It was during their tenure as Co-op students at the NASA Dryden Flight Research Center that they developed this desire and their continued interest in that regard was well received by Mr. Chuck Brown and Mr. Larry Schilling of NASA Dryden as well as by Dr. Shaik Jeelani of Tuskegee University. In part, their desire has materialized into the research project covered by this report. Dennis has continued to show exemplary devotion to the flight simulation program and has given noteworthy help in editing this report.

I extend my sincere gratitude to all those whose guidance, support, help, and good wishes have resulted in the completion of a phase of research work that is reported here.

Syed Firasat Ali,
Principal Investigator

TABLE OF CONTENTS

| | |
|------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Abstract | i |
| Acknowledgments | ii |
| List of Figures and Tables | iv |
| Introduction | 1 |
| The Simulation System | 1 |
| Flight Data Processing | 2 |
| The Pilots and the Test Flights | 3 |
| Flight Test Results | 4 |
| Conclusions | 17 |
| Nomenclature | 18 |
| References | 19 |
| Appendix A: The Graphs of the Raw Data for the Five Selected Flights. | A 1 |
| Appendix B: Copy of the paper; " <i>Pilot Input and Airplane Response Cross Correlations On a Flight Simulator With and Without Transport Delay.</i> " | B 1 |

LIST OF FIGURES AND TABLES

| <u>Figures:</u> | <u>Page:</u> |
|------------------------------------------------------------------------------------|---------------------|
| Figure 1: Correlation Between Elevator Deflection and Time Derivative of Altitude. | 9 |
| Figure 2: Correlation Between Elevator Deflection and Airplane Altitude. | 10 |
| Figure 3: Correlation Between Elevator Deflection and Airplane Heading. | 11 |
| Figure 4: Correlation Between Aileron Deflection and Airplane Heading. | 12 |
| Figure 5: Correlation Between Rudder Deflection and Airplane Heading. | 13 |
| Figure 6: Correlation Between Deflections of Elevator and Ailerons. | 14 |
| Figure 7: Correlation Between Deflections of Elevator and Rudder. | 15 |
| Figure 8: Correlation Between Deflections of Rudder and Ailerons. | 16 |
| <u>Tables:</u> | |
| Table I: Comparison of Pilots' Performance in Their Best Flights. | 8 |

INTRODUCTION

McRuer and Graham (1981) have presented a survey of eighty years of flight control, and Ashkenaz (1984) has presented a survey of twenty five years of handling qualities research. From both survey presentations, it appears that prior to 1984, the cross correlations between pilot inputs and airplane response on a real time simulator had not been studied, but transfer functions representing human pilots had been proposed (see, for example, Washizu and Miyajima, 1965, and Smith, 1965), and the pilot induced oscillation (PIO) theory and resulting prediction technique had been developed (see Smith, 1977). The prediction techniques were tested on eighteen aircraft/flight control system landing configurations by Bjorkman (1986). Bjorkman indicated the need of more data and simulator studies to gain physical insights into PIO mechanization. From more recent works on PIO including the paper by Hess and Kalteis (1990), the need of more data is further desired. Cardullo et al, and Middendorf et al are some of the recent studies on the effect of simulator transport delay on pilot's performance. In the present work a low cost flight simulator system with graphics and software on computer workstations has been installed. On the simulation system, a future study of PIO is proposed. As preparatory work for a future PIO study, the flight data has been obtained for two sets of flights with pilot in the loop. For conducting their flights, the pilots utilized the heads-up display on the computer monitor and operated a joystick to maintain a given altitude and a given heading. One set of flights is obtained without any additional delay between the stick input and the appearance of airplane response on the computer monitor. In another set of flights, a 500 ms additional delay is used. The flight data has been processed to find cross correlations between deflections of control surfaces and response of the airplane. It is anticipated that these cross correlations for straight level flights would serve as reference material to compare the respective cross correlations for future simulator studies of PIO. A portion of the work of this report was presented at an AIAA Southeastern Student Conference By Williams and Johnson (1997), and their paper is included as Appendix B in this report. While the test flights for the present study were being conducted, the raw data on some of them were displayed on the internet at <http://silicon.tusk.edu/~jpwll>.

THE SIMULATION SYSTEM

The simulation system is comprised of two SGI workstations and a BG System Joystick called a FlyBox. The two workstations are SGI IRIS with 2 CPUs and SGI Indigo 2 with one CPU; they are connected through ethernet. The simulation software, which represents the dynamics of flight of an F-15E jet fighter has been provided by NASA Dryden Flight Research Center. For the graphics of the system, the graphics of the SGI flight simulation demos has been integrated with the software of the airplane dynamics. Norlin (1995) has provided a description of the design of software, and its

simulation capabilities. According to Norlin, the F-15E real-time simulation is coded with a FORTRAN 77 shell and C support routines and it operates on a UNIX-based multiprocessor computer. The FORTRAN code includes the aircraft models, equations of motion, integration table look-ups, initialization and display generation routines. The C support routines are used for the graphical user interface, memory mapping, priority boosting, and interrupt handlers. In addition, C is used for the graphics and distributed system functions. The integration scheme is optimized for real-time operation. In this method, the derivatives are only calculated once for each frame, a weighted average of the midpoint and previous frame derivative is used to predict the derivative at the end of the frame. The equations of motion assume flat earth and six degrees of freedom. The airplane is assumed symmetrical about its own x-z plane. The simulation model calculations and integration of the equations are performed in the real-time loop. For pilot in the loop or hardware in the loop, the main real-time task is interrupt driven at the highest allowable system priority. The use of 3 CPUs ensures that timing constraints are adequately met. For their simulators, NASA Dryden prefer to use the name engineering simulators instead of production training simulators. The engineering simulators provide high fidelity simulation that is responsive to the needs of the researchers. The F-15E simulator used in the present work is an engineering simulator. It is called the F-15 ACTIVE which implies that it incorporates Advanced Control Technology for Integrated Vehicles. The code has the flexibility to program a desired transport delay between the stick input and the airplane response on the monitor. The use of UNIX "makefiles" to compile the simulation allows minor updates within about 5 minutes. The joystick has three different movements to deflect the three control surfaces: forward-rearward movement for elevator deflection, right-left movement for aileron, and clockwise-counterclockwise rotation about its own axis to simulate pedal movement for rudder deflection. It may be noted that the experienced pilots would prefer the use of rudder pedals instead of the existing stick movements to simulate the pedal movements, therefore, the absence of pedals may cause a lack of coordination between the rudder and ailerons in their test flights during simulation. In a simulated flight, the digital data on forty two different flight parameters can be recorded at every 25 ms time intervals. The flight parameters include altitude (H), time rate of change of altitude (HDOT), and heading (PSI) as well as stick deflection for elevator (DEP), stick deflection for aileron (DAP), and pedal movement for rudder (DRP). A pull on the stick or a positive value of DEP deflects the elevator upward which raises the nose of the airplane and increases its altitude (see, for example, Roskam 1995, p. 241). In the present report the DEP, DAP, and DRP data are essentially used to find cross correlations. It is understood that the deflections of elevator, aileron, and rudder are proportional to the values of DEP, DAP, and DRP, respectively. Therefore, for computing the dimensionless cross correlation coefficients, the values of DEP, DAP, and DRP are treated as relative values of deflections of elevator, ailerons, and rudder although the dimensional values of DEP, DAP, and DRP are not the dimensional values of deflections of the respective control surfaces.

FLIGHT DATA PROCESSING

In the present study, all flights conducted on the simulator were straight level flights of three minute duration. For any flight conducted, the simulator can provide digital data for 42 flight parameters at every 25 ms time interval. For the present work, however, the digital data was obtained for only altitude (ft.), heading (deg.), time derivative of altitude (ft./sec.), and the deflections of elevator, rudder, and aileron. For the altitude, H represents its instantaneous value and h represents the fluctuating part of its instantaneous value. Therefore,

$$h(t) = H(t) - \text{avg. } H$$

where the avg. H is the average altitude of the three minute flight and t represents time.

For the heading, Ψ represents its instantaneous value and ψ represents the fluctuating part of its instantaneous value. Therefore,

$$\psi(t) = \Psi(t) - \text{avg. } \Psi$$

Similar relations are used between instantaneous values, fluctuating values and average values of the control surface deflections. Δ is used for instantaneous value of control surface deflection, and δ for the fluctuating part of the instantaneous value. For distinction between the three control surface deflections, the subscripts a and r represent aileron and rudder, respectively. No subscript is used on Δ or δ to indicate elevator. The rms values of the above signals are denoted by, δ' , h' , and ψ' . The coefficient of cross correlations between δ and h for an arbitrary time gap τ is denoted as $\text{CORR}(\tau)$ and it is defined as:

$$\text{CORR}(\tau) = \frac{1}{T \delta' h'} \int_{t=0}^{t=T} \delta(t) h(t + \tau) dt$$

The simulator provides data at every 25 ms interval, thus a 3 minute flight has 7201 points for each signal. The coefficient of cross correlation is therefore calculated as follows:

$$\text{CORR}(j) = \frac{1}{(7200 - j) \delta' h'} \sum_{i=1}^{(7201-j)} \delta_i' h_{i+j}$$

To cover a time gap, τ of 20 seconds, $\text{CORR}(j)$ is calculated for $j = 1, 2, \dots, 801$. For 100 second time gap j ranges from 1 to 4001. It is suggested that care be exercised in interpreting the long time gap correlations. For the correlation with zero time gap, the averaging is based on 7200 pts, with 20 second time gap the averaging is based on 6400 points, and with 100 second time gap the averaging is based on 3200 points. The cross correlation coefficients between any other two signals are defined and calculated in the same manner. In the above formulas δ and h may be replaced by any other two signals between which the cross correlation is desired. In the present work, the cross correlations are considered between δ and h , δ and dh/dt , δ_r and ψ , δ_a and ψ , δ_r and δ , δ_a and δ , δ_r and δ_a .

THE PILOTS AND THE TEST FLIGHTS

Four volunteer pilots conducted the required flights on the F-15E real-time simulation. Three of them were experienced licensed pilots and one had no prior experience of flying. In this report, the volunteer pilots are named P1, P2, P3, and P4. The ages, flying hours, and the license status of the pilots were P1: 69 yrs, 3200 hrs, SEL, MEL, INST; P2: 48 yrs, 100 hrs, SEL, MEL, INST; P3: 23 yrs, 830 hrs, SEL, MEL, INST; and P4: 26 yrs, no flying experience.

In every test flight, a pilot was required to maintain straight level flight for three minutes duration heading due North, with preadjusted throttle for flying at 450 knots indicated at 10,000 ft. altitude with autotrim OFF. During the flight, the pilot inputs were limited to the joystick movements only. The volunteer pilots were provided with the facility to train themselves on the simulator by conducting several three minute flights until they reached their own asymptotic performance in terms of $(h' + 10\psi')$ a weighted sum of the rms values of fluctuations in altitude and heading in ft. and deg. respectively. Every pilot conducted two sets of straight level flights. One set of flights was obtained without any additional delay between the stick input and the appearance of airplane response on the computer monitor. In another set of flights, a 500 ms additional delay was used. Including the flights with the asymptotic performance, the pilot P1 conducted 15 flights without delay and 15 flights with delay; P2 conducted 16 flights without delay and 21 flights with delay; P3 conducted 22 flights without delay and 17 flights with delay; and P4 conducted 40 flights without delay and 25 flights with delay. From amongst the asymptotic performance flights, for each of the two kinds of flights, and for each pilot, based on the value of $(h' + 10\psi')$, the best flight, the average flight, and the worst flight were picked up for further analysis. For all twenty four of these flights,

Williams and Johnson (1997) have reported average values and rms values of altitude and heading and δ -h correlation versus time gap graphs.

A comparison of the average and rms values of altitude and heading for the four pilots indicated that the pilots P3 and P4 had remarkably small deviations, whereas pilots P1 and P2 had rather large deviations from the desired values. It is believed that the cross correlations between any two randomly changing but related variables would be better representative of their mutual interdependence if their deviations from the desired quantities are rather small. Therefore the correlations for the flights of pilots P1 and P2 are not reported here due to their large deviations in δ and h. They may instead be seen in Williams and Johnson's paper provided in Appendix B. In the main report, the discussions on correlations dwell upon five different flights and those are the best flights of pilots P3 and P4 without delay, the best flights of pilots P3 and P4 with delay, and the average flight of pilot P3 with delay. The average flight of pilot P3 with delay is included in the discussion because the best flight of P3 showed an unusual correlation feature when compared with the other flights of pilots P3 and P4. The graphs of the raw data for these selected five flights are provided in Appendix A.

FLIGHT TEST RESULTS

For comparison of pilot's performance in flights without transport delay and those with 500 ms delay, the rms values of altitude and elevator deflections for the best flights of the four pilots are shown in Table I. For both kinds of flights, pilots P3 and P4 have achieved better performance compared with pilots P1 and P2. For the flights of pilots P3 and P4, the rms values of altitude and elevator deflection for flights with delay are approximately twice their respective values for flights without delay. It is obvious that the 500 ms transport delay has resulted in deteriorated pilot's performance. With the existing related publications in view, this is not surprising. For example, Middendorf et al (1991) have noted that 300 ms transport delay resulted in significant deterioration of pilot's performance.

In a study of pilot dynamics and pilot's choices of feedback alternatives for controlling altitude, the frequency response functions of pitch angle and altitude have been obtained and used by Goto and Matsuo (1988). In the present work, the cross correlations between the control surface deflections and airplane responses are obtained to understand some aspects of the pilot dynamics. Let us start with the consideration of cross correlations between elevator deflection, δ and airplane altitude, h. An upward instantaneous deflection of elevator from its average deflection is positive δ and a downward deflection is negative δ , although the convention is to take downward elevator deflection as positive, for example Etkin and Reid (1996, p. 33). A higher instantaneous altitude compared with the average altitude of the three minute flight is positive h, and a lower than average is negative h. It is understood

that a positive change in δ results in a positive change in h and a negative change in δ results in a negative change in h . Allowing for a time lag between elevator deflection and altitude response, the two signals δ and h should have a positive correlation.

Figure 1 presents δ - h correlations for pilots P3 and P4 for a range of time gaps between zero and 20 seconds. Figure 1 has the graphs for the five selected flights, their selection is indicated in the previous section. All the flights of Figure 1 have a common feature - that they do not have large deviations from the required altitude of 10,000 ft; the maximum deviation in average altitude is 6 ft. in the best flight of pilot P4. All the flights show an appreciable magnitude of negative δ - h correlation for zero time gap. This is expected because upon noticing positive h , the pilot moves the stick to deflect the elevator downward and vice versa.

Let us consider the best flight without transport delay for pilot P3 as a typical one amongst the five flights of Figure 1. In this flight the largest magnitude of negative correlation is reached when the time gap is 400 ms; to talk about it, let us call it the first time gap on the graph. The first time gap, perhaps, includes three stages of airplane altitude control: the pilot's reaction time, the time gap between stick movement and the resulting elevator deflection, and the time gap between elevator deflection and affected altitude change. This consideration appears reasonable when it is seen with Roskam's (1995, p.765) assumptions of 100 ms reaction time for test pilots and 120 to 200 ms reaction time for other pilots. The correlation stays negative up to 2700 ms. Let the second time gap on the correlation graph be the time gap between the largest negative magnitude of correlation and zero correlation, here it is $2700 - 400 = 2300$ ms. The second time gap, perhaps, represents limitations on the rates of climb and descent; higher rates would lead to lower value of the second time gap. With transport delay, the best flight of pilot P3 has an exceptional feature that its' first time gap is zero; this exceptional feature is not explored further. The raw data in Appendix A, however, shows no significant differences in the best and average flights of pilot P3 with delay; but the elevator deflections for the first 30 seconds in the flights with delay are different from the respective values in the flight without delay. Due to the exceptional nature of the best flight of pilot P3 with delay, the average flight of P3 is included in Figure 1 to be discussed as another typical flight with delay. Four of the five flights in Figure 1 may be treated as typical straight level flights; for them the first time gap ranges from 350 ms to 600 ms and the second time gap ranges from 2300 ms to 5700 ms. One of the reasons for large differences in the first and second time gap values for different flights may be that pilot's observations and actions are continuous rather than discrete in nature; the pilot does not need to wait until elevator deflection or airplane response corresponds with certain stick movement. The largest magnitudes of correlation coefficients and the first and second time gaps are not significantly affected by the 500 ms transport delay. This is surprising, especially when we note that the rms values of fluctuations of altitude and elevator deflection in flights with transport delay are approximately twice the corresponding values in flights with no delay. The respective rms values are

provided in Figure 1. It is understood that a change in elevator deflection causes a pitching moment that brings about a rate of change of airplane altitude. Therefore, for a more clear view of certain features of the same flights, to substantiate the δ -h correlations of Figure 1, the δ -h \dot{d} ($\dot{h} = dh/dt$) correlations are provided in Figure 2.

In Figure 2, all the flights, except the best flight with transport delay for pilot P3, show an appreciable negative δ -h \dot{d} correlation at zero time gap. This is expected because upon noticing positive \dot{h} above the required 10,000 ft. altitude, the pilot moves the stick to deflect the elevator downward, and upon noticing negative \dot{h} below 10,000 ft. he moves the stick to deflect the elevator upward. The negative values of δ -h \dot{d} correlations at zero time gap in Figure 2 are less in magnitude than the corresponding δ -h correlations in Figure 1. This is understood because upon noticing positive \dot{h} for altitude below 10,000 ft. and negative \dot{h} for altitude above 10,000 ft., the pilot does not need to change the elevator deflection.

In the best flight of P3 without transport delay, picked up here as a typical flight, the correlation reaches zero when the time gap is 400 ms. For the same flight, this reinforces the observation that the largest magnitude of negative δ -h correlation occurred at the same time gap as seen in Figure 1. In all the graphs of Figure 1 and Figure 2, it is noticeable that the δ -h \dot{d} correlation becomes zero at the same time gaps at which the δ -h correlations have local maximum or minimum values.

In Figure 2, let us consider the two flights of pilot P4. For the δ -h \dot{d} correlations the number of zero crossings in 20 seconds for the flight with transport delay is twice that for the flight without transport delay. A similar feature is not found in the two kinds of flights for pilot P3. It may be reiterated here that pilot P3 is a certified and experienced pilot whereas the experience of pilot P4 is limited to flight simulators only. From Figure 1, we recall that the first time gap goes from zero to a value where the magnitude of negative correlation is largest and the second time gap goes from the end of the first gap to a value where the correlation is zero. Let the subsequent time gaps represent the subsequent zero crossings of the correlation starting from the first zero crossing. Perhaps the time gaps between the consecutive zero crossings would provide an indicator of the pilot's performance, larger gaps representing better or more steady performance provided that the deviation in altitude stays small. Such an indication is jeopardized to a certain degree because stick signal in the flights under study is contaminated by electronic noise. For elevator and aileron deflections, the noise signal is estimated at 3% of a typical stick movement. For rudder deflection, the signal is significantly larger than 3%. No attempt is made to suppress or filter out this noise because it requires the pilot to remain vigilant if he wishes to maintain the straight level flight. To find the subsequent zero crossings of the δ -h correlations, the graphs are obtained for time gaps from 0 to 100 seconds. For the same flights which are included in Figure 1, the 100 second graphs are shown in Figure 3. As suggested in the section on Flight Data Processing, care is needed in interpreting the long time gap correlations. In Figure 3, for

the time gap range from zero to 100 seconds, for pilot P3, a flight with transport delay has 5 zero crossings and a flight without delay has 16 zero crossings. On the contrary, for pilot P4, a flight with transport delay has 24 zero crossings and a flight without delay has 7 zero crossings. Using Lanchester's estimate (reference Etkin and Reid 1996, p. 172), the time period for phugoid oscillations at 450 kts. or 760 ft./s is 104 sec. which implies nearly 2 zero crossings in 100 seconds. It is not clear if the phugoid oscillations have a role here. Based on rms values of h and δ fluctuations only, the performance of both pilots is nearly the same. Having fewer zero crossings in flights without delay as compared with the ones with delay is intuitively more acceptable. Therefore, the performance of pilot P4 is somewhat predictable but that of P3 is surprising. It may be interesting to reiterate that pilot P3 is a licensed and experienced pilot but the experience of P4 is limited to flight simulators only.

Figure 4 shows the coefficient of cross correlation between aileron deflections and airplane heading versus time gap for the same five selected flights which have been covered in Figure 1. For four of the flights the graphs have similar features. For all the five flights, the largest magnitude of the negative correlation occurs at the time gap values between 450 ms and 725 ms. This time gap range is comparable with 350 to 650 ms, which is the first time gap range for δ - h correlations in Figure 1. For zero time gap, an appreciable negative correlation exists in all the five flights. For both pilots, the rms values of aileron deflections for flights with delay are appreciably larger compared with those for flights without delay. The rms values of airplane heading do not have the same character as that of the rms values of aileron deflections.

Figure 5 provides the coefficient of cross correlation between rudder deflection and airplane heading versus time gap. In the best and average flights with delay for pilot P3 appreciable changes appear in the correlation with time gap. In the rest of the three flights the correlation is rather insensitive to the time gap. The raw data in Appendix A helps to trace this insensitivity to an inactivity on the pilot's part in using the rudder for heading control. The pilot P3 has used rudder movement much more than pilot P4. For the average flight of pilot P3 with delay, the rudder-heading correlation in Figure 5 has similar features as the aileron-heading correlation in Figure 4. This similarity may be an indicator of coordinated use of rudder and ailerons.

Figure 6 has the coefficient of cross correlation between elevator deflection and aileron deflection versus time gap. The correlation for the five flights does not seem to have any common features except that the correlation is rapidly changing between positive and negative values.

Figure 7 has coefficient of cross correlation between elevator deflection and rudder deflection versus time gap. Four of the five flights show appreciable negative correlations for zero time gap, although

such a feature between the movements of elevator and aileron may not be worth emphasizing. In general, the correlation graphs for the five flights do not have any common features.

Figure 8 presents the coefficient of cross correlation between rudder deflection and aileron deflection versus time gap. For different flights, at zero time gap, the different values of correlation coefficient appear to represent the pilot's coordinated use of rudder and aileron. No common features are discernable between different flights, perhaps, because of the lack of use of the rudder by the pilots. The hardware facility in the present simulation system, perhaps, demotivated pilots from using the rudder. The system hardware does not have rudder pedals, instead, the rudder pedal movement is simulated by the rotation of the joystick as described in the section on "The Simulation System."

An overall consideration of all the correlation graphs suggests that for reasonably well defined flights, the cross correlations between pilot input and airplane response versus time gap reveal interesting features of the pilot dynamics. When the aileron-heading and the rudder-heading correlations for a flight are considered together, they reveal the presence or absence of coordinated use of ailerons and rudder by the pilot. Consideration of correlations amongst the parameters that represent longitudinal motion of the airplane and correlations amongst the parameters that represent lateral motion of the airplane support the generally used approach of separate studies of longitudinal and lateral dynamics of an airplane in flight.

Additional research work may be recommended to find certain characteristic features of cross correlations between pilot input and airplane response. Such characteristic features would then help in determining different progressive stages of pilot training on simulators.

| Pilot | h_n' | δ_n' | h_d' | δ_d' |
|-------|--------|-------------|--------|-------------|
| P1 | 73.8 | 0.60 | 77.1 | 1.02 |
| P2 | 51.2 | 0.51 | 66.4 | 0.20 |
| P3 | 7.5 | 0.23 | 18.2 | 0.45 |
| P4 | 9.4 | 0.25 | 18.7 | 0.72 |

Table I: Comparison of the Pilot's Performance in Their Best Flights With and Without Transport Delay, h' and δ' are the rms values of altitude changes and elevator deflection changes, respectively, subscript n is used for flights with no delay and d is used for flights with 500 ms delay.

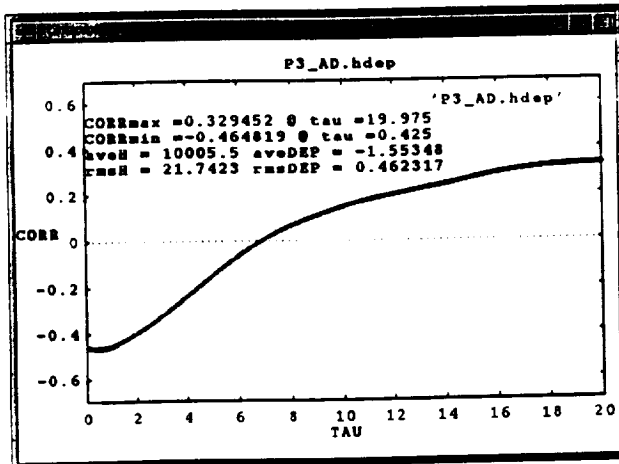
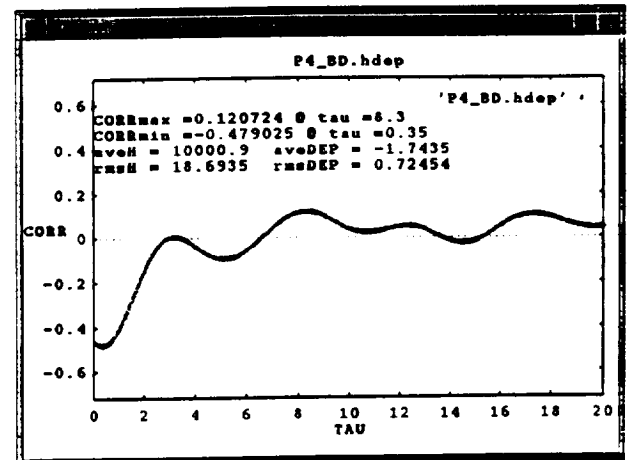
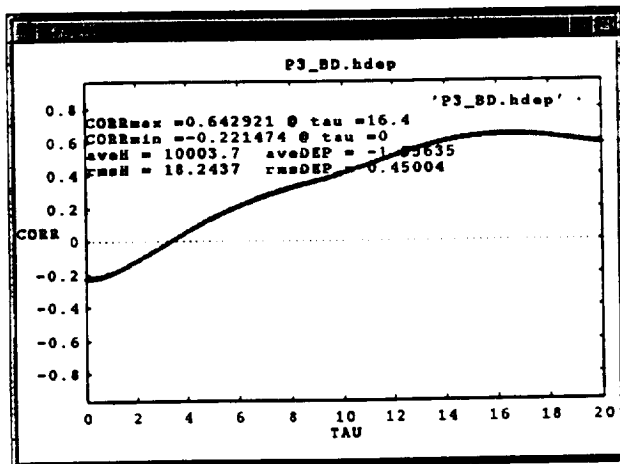
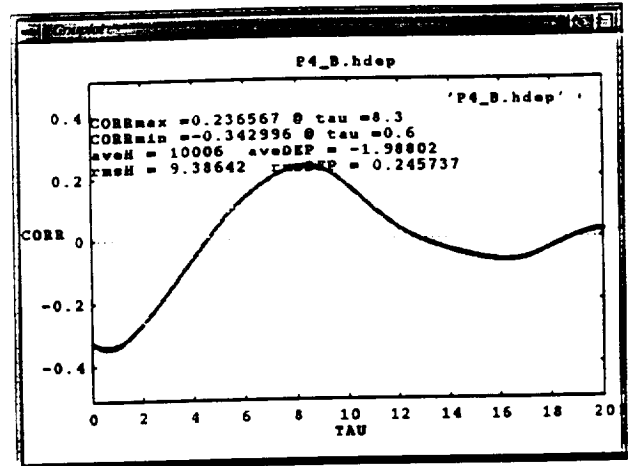
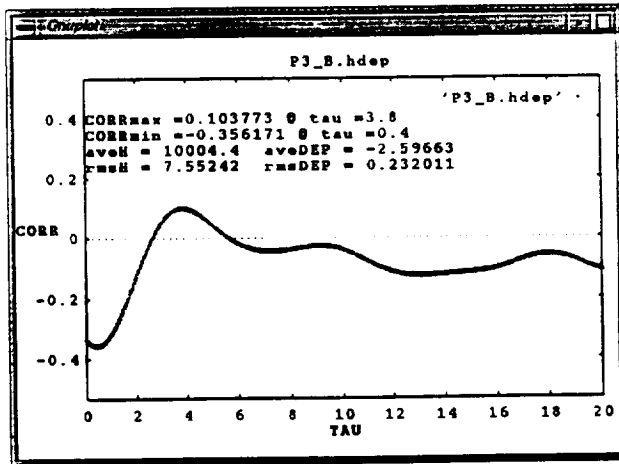


Figure 1: Cross Correlation Coefficient Between δ and h vs. τ for the Five Selected Flights of Pilots P3 and P4. B is the pilot's best flight without additional transport delay. BD and AD are the pilot's best and average flights with additional transport delay of 500 ms. (δ = elevator deflection, h = airplane altitude, τ = time gap).

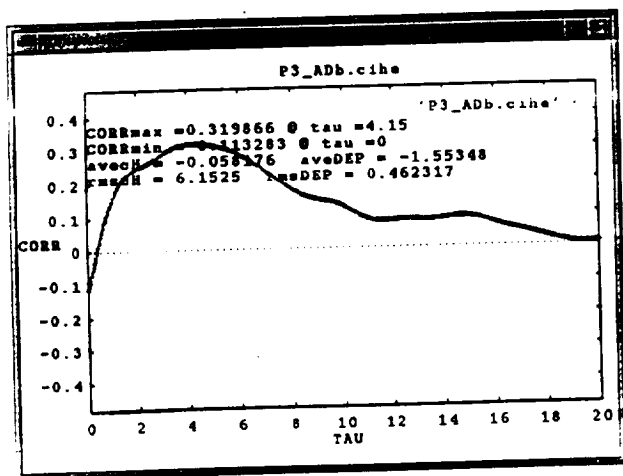
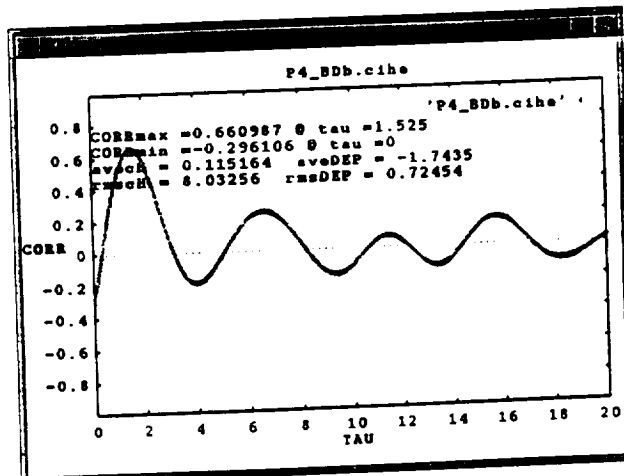
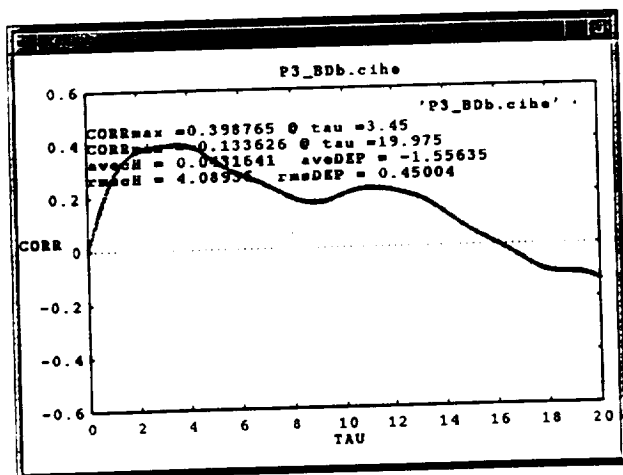
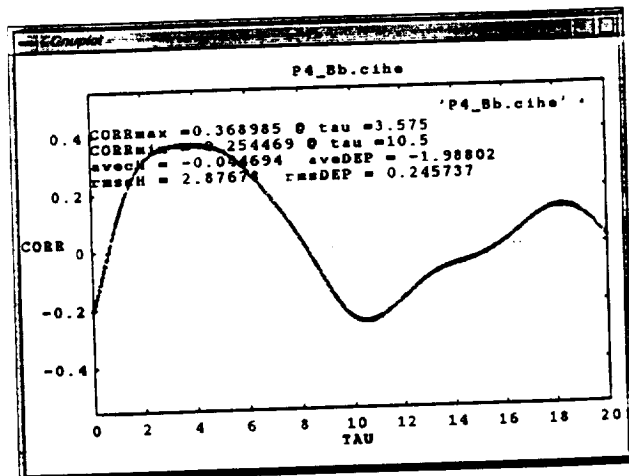
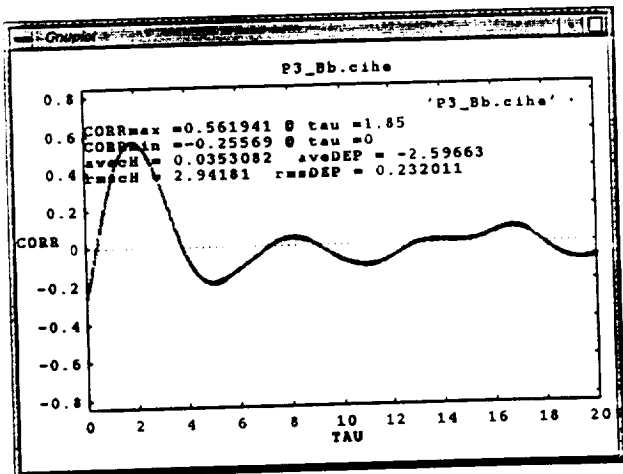


Figure 2: Cross Correlation Coefficient Between δ and dh/dt vs. τ for the Same Selected Flights Which Are Covered in Figure 1. (δ = elevator deflection, h = airplane altitude).

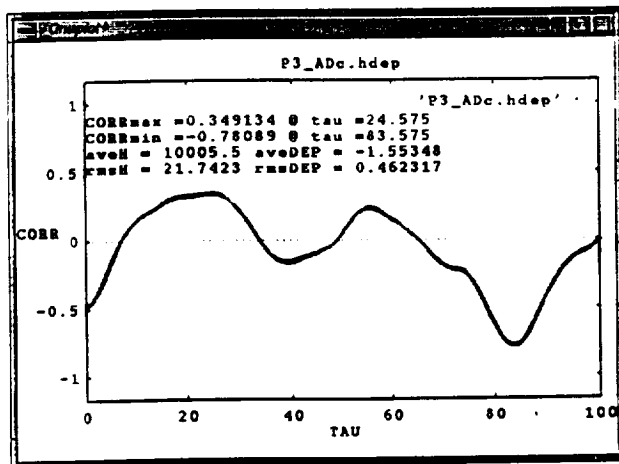
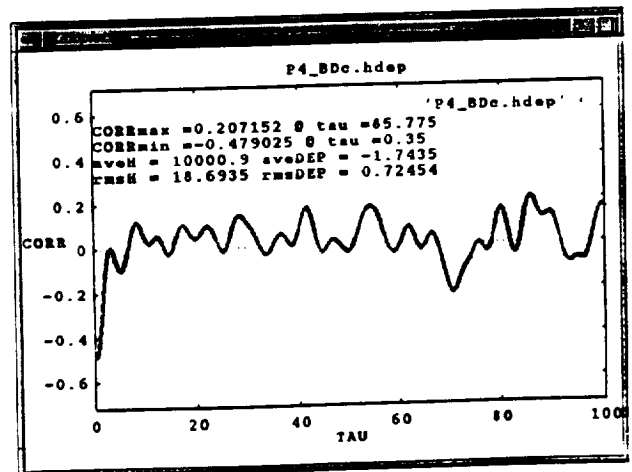
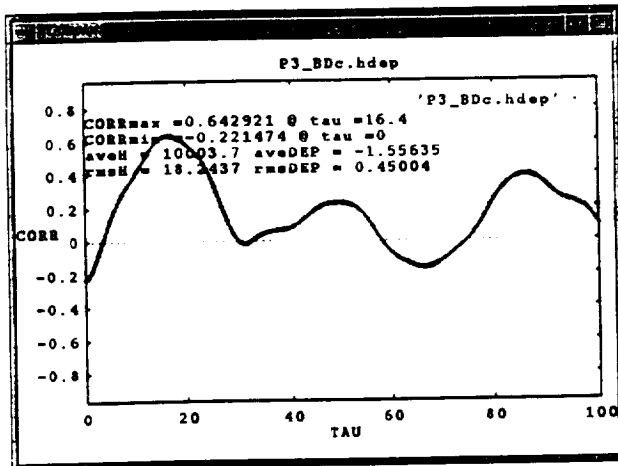
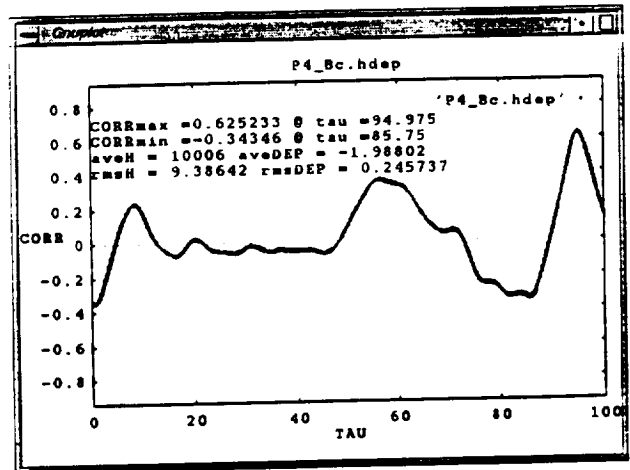
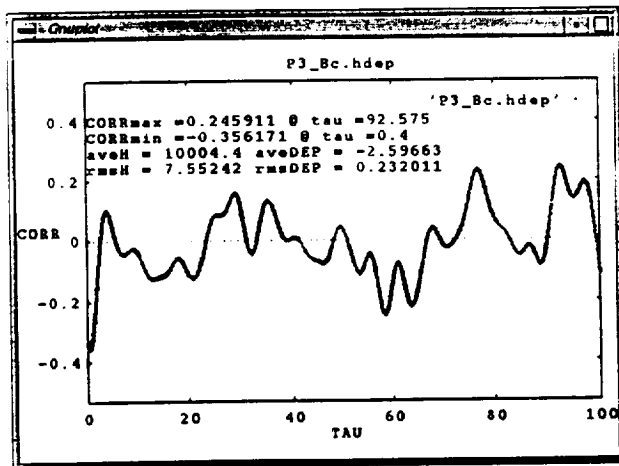


Figure 3: Cross Correlation Coefficient Between δ and h vs. τ for τ up to 100 Seconds. For the same flights, τ goes up to 20 seconds in Figure 1. (δ = elevator deflection, h = airplane altitude).

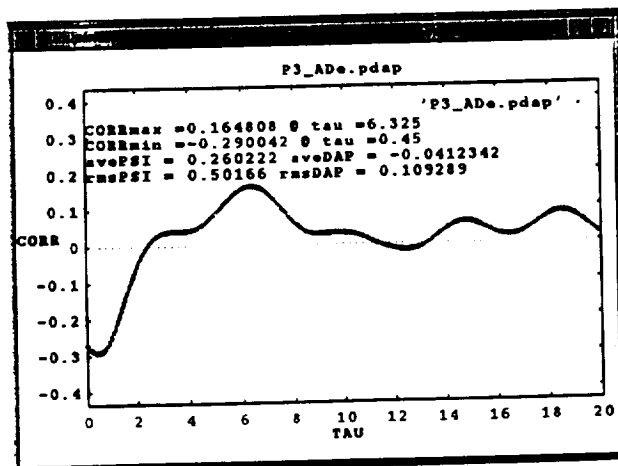
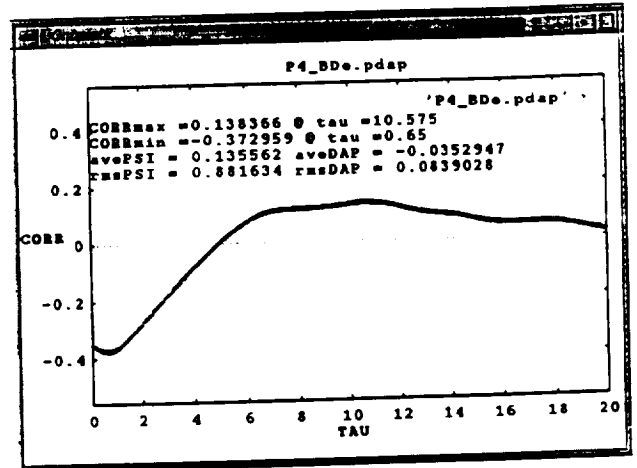
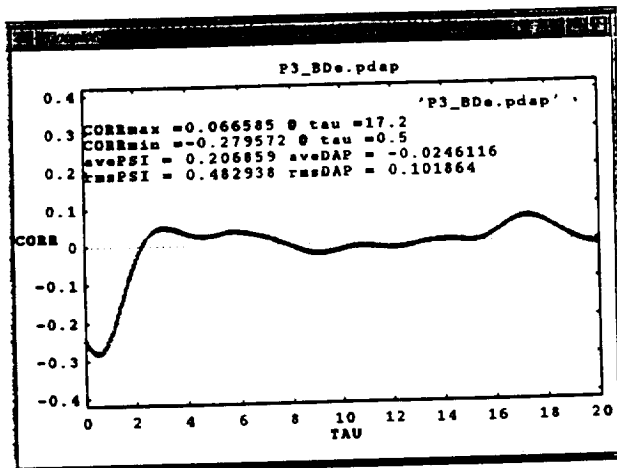
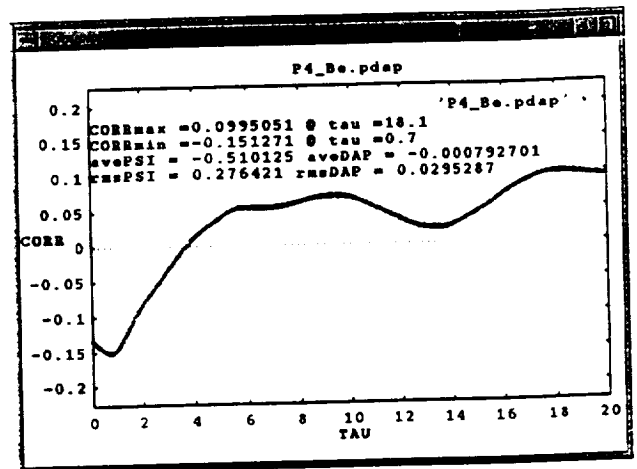
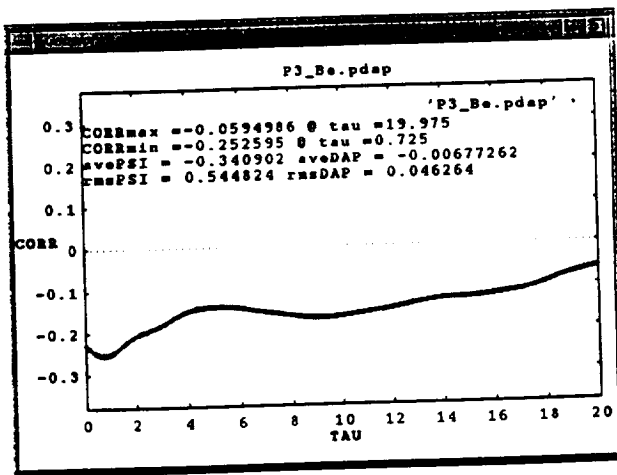


Figure 4: Cross Correlation Coefficient Between δ_a and ψ vs. τ for the Same Selected Flights Which Are Covered in Figure 1. (δ_a = aileron deflection. ψ = airplane heading).

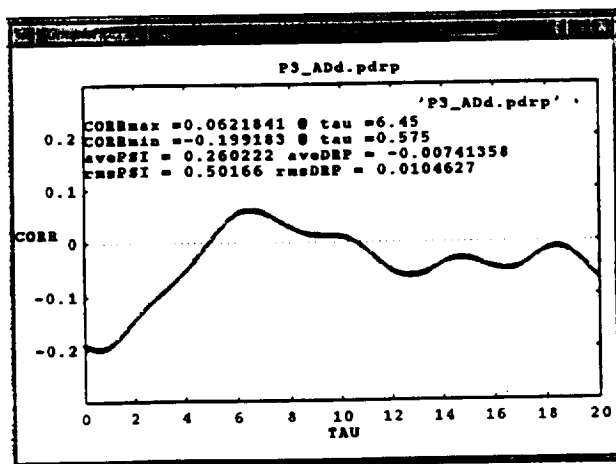
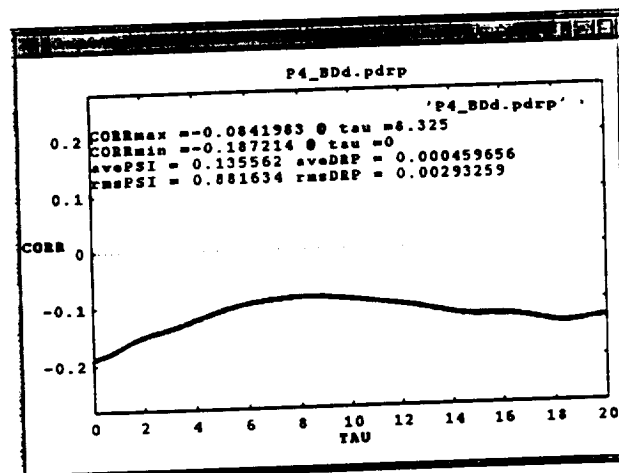
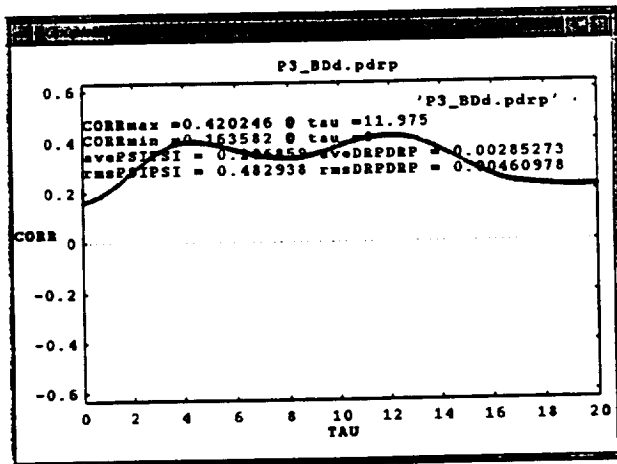
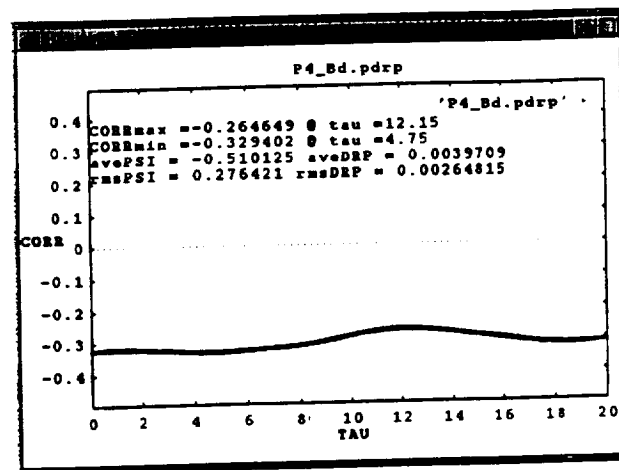
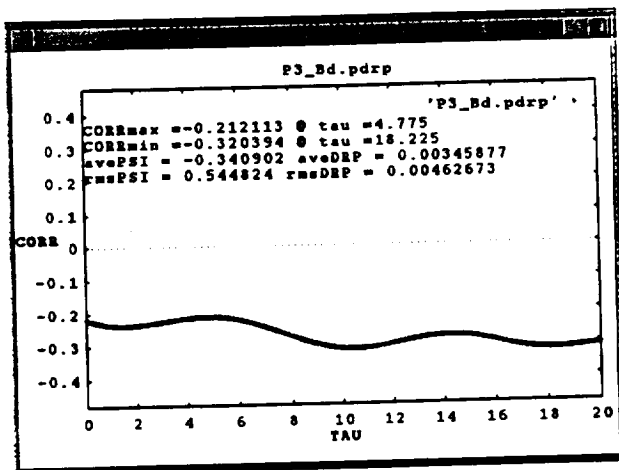


Figure 5: Cross Correlation Coefficient Between δ , and ψ vs. τ for the Same Selected Flights Which Are Covered in Figure 1. (δ = rudder deflection, ψ = airplane heading).

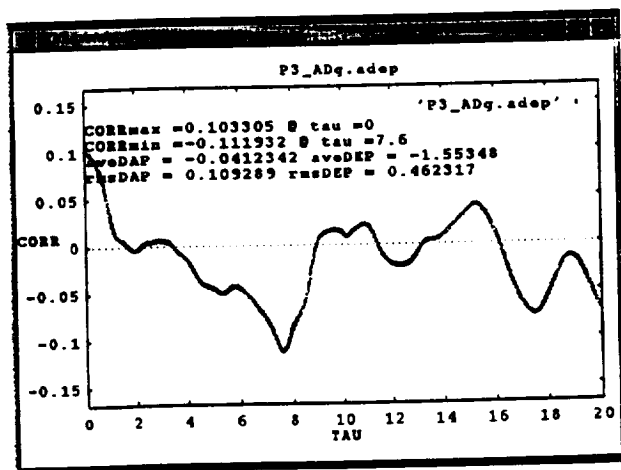
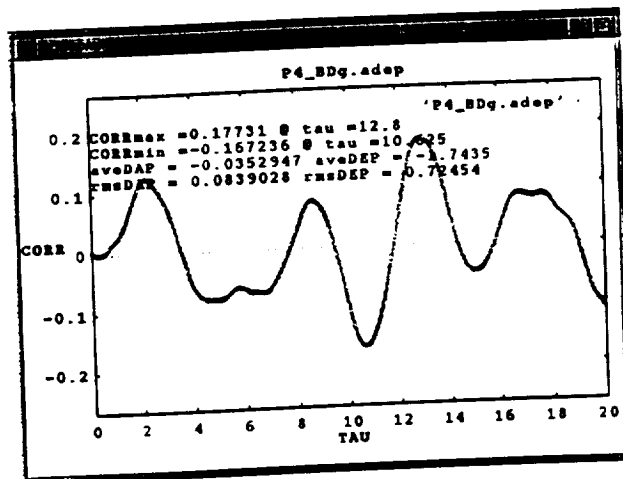
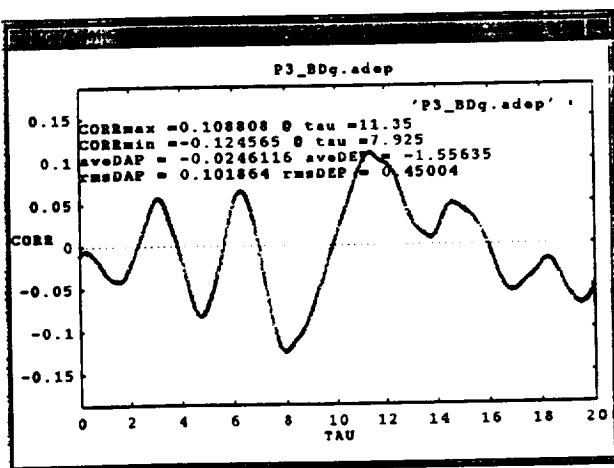
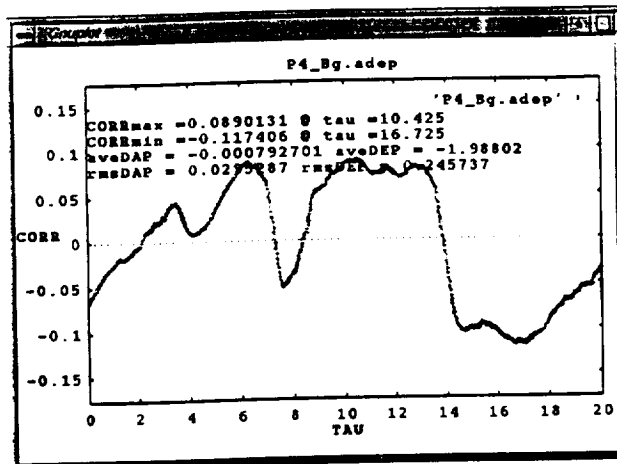
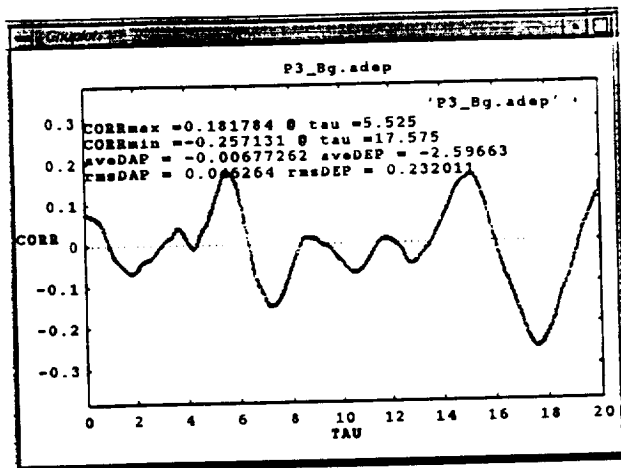


Figure 6: Cross Correlation Coefficient Between δ and δ_a vs. τ for the Same Selected Flights Which Are Covered in Figure 1. (δ = elevator deflection, δ_a = aileron deflection).

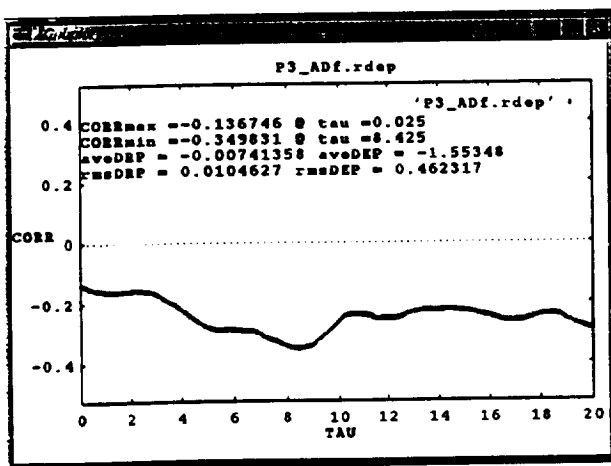
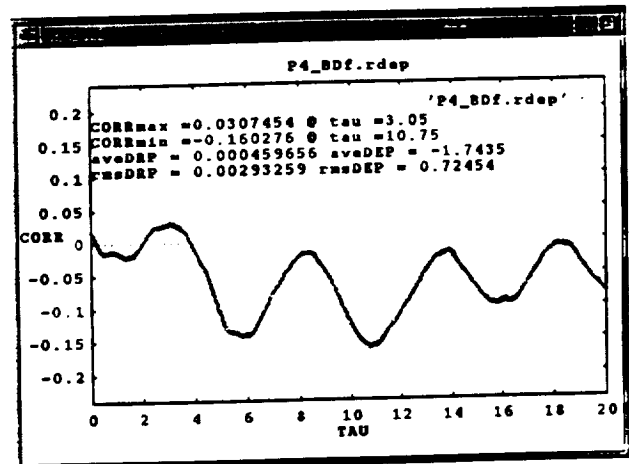
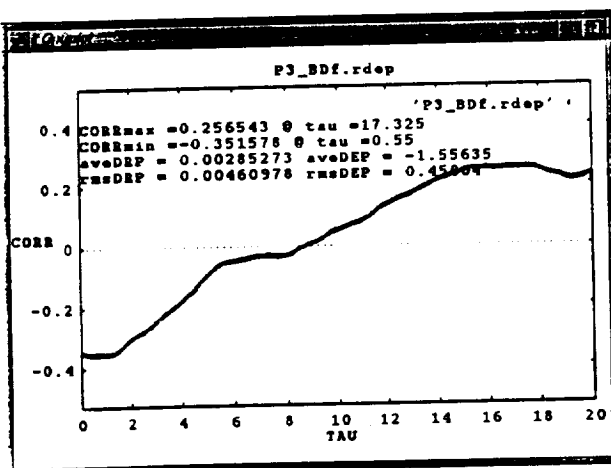
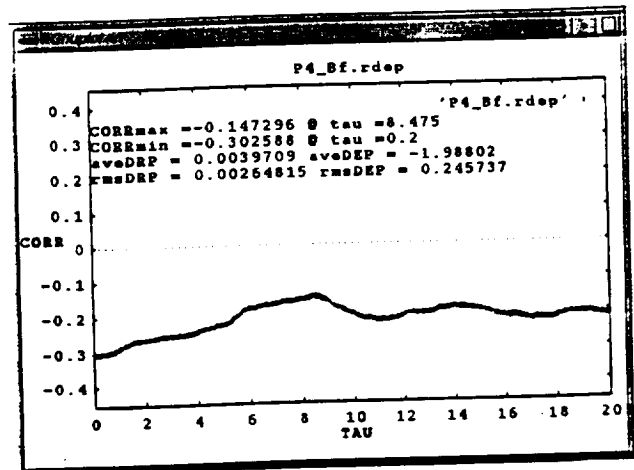
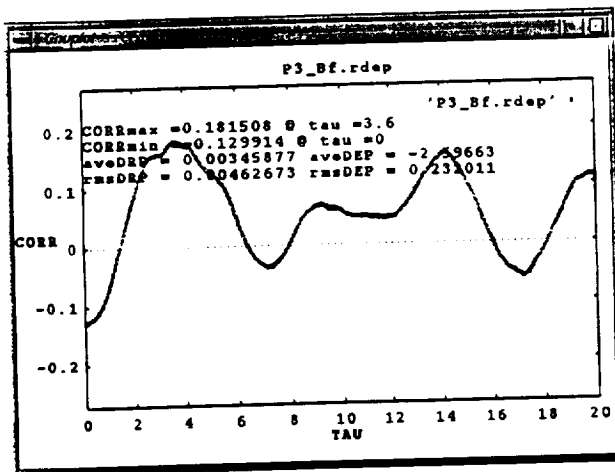


Figure 7: Cross Correlation Coefficient Between δ and δ_r vs. τ for the Same Selected Flights Which Are Covered in Figure 1. (δ = elevator deflection, δ_r = rudder deflection).

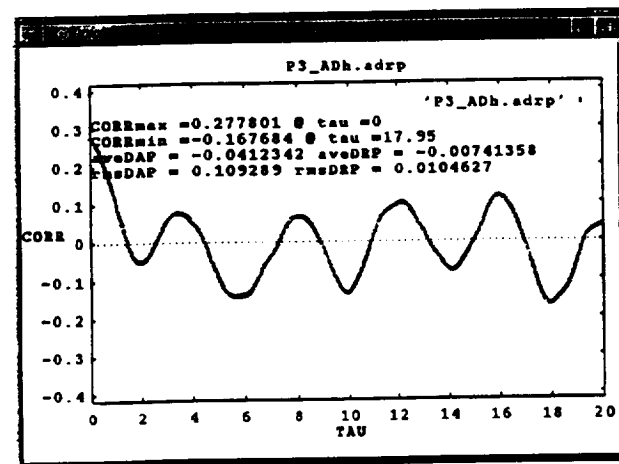
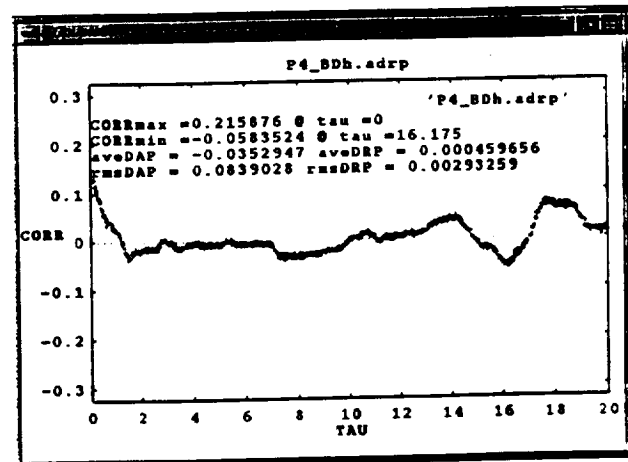
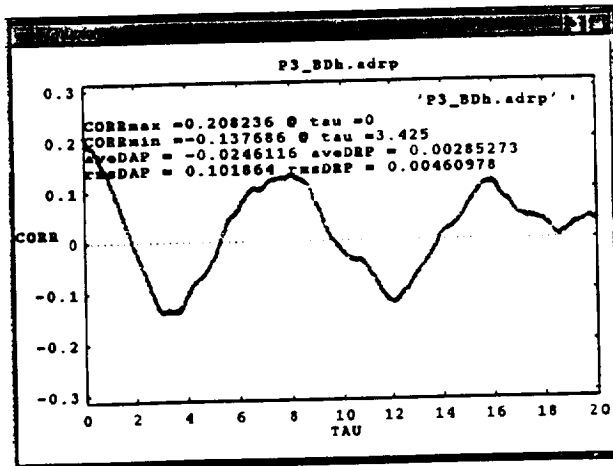
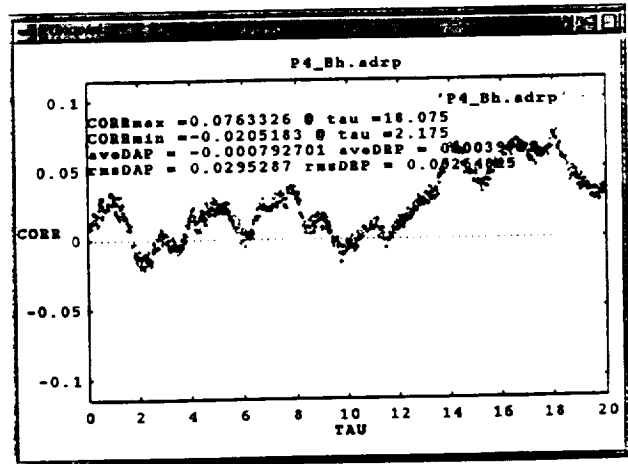
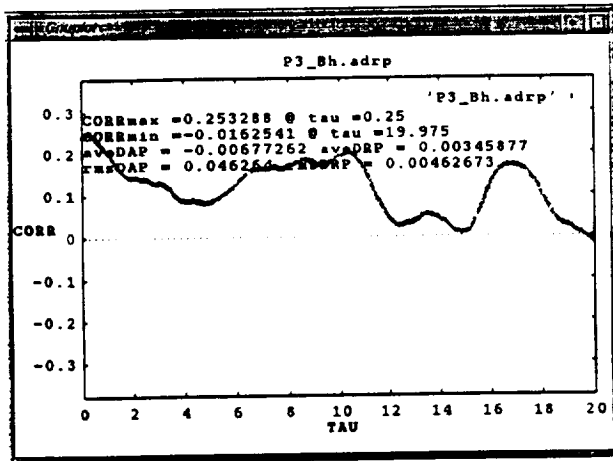


Figure 8: Cross Correlation Coefficient Between δ_r and δ_a vs. τ for the Same Selected Flights Which Are Covered in Figure 1. (δ_r = rudder deflection, δ_a = aileron deflection).

CONCLUSION

In the study of straight level flights on a simulator with pilot in the loop, the root mean square values of altitude variations for flights with a 500 ms additional delay are twice or larger compared with their respective values for flights with no delay. This is in agreement with the other recent studies which indicate deterioration in flight with 300 ms transport delay. The graphs of cross correlations between pilot input and airplane response versus time gap reveal interesting features of the pilot dynamics. A time gap of 350 to 600 ms appears to include three steps of altitude control, these are pilot's reaction time, time gap between stick movement and resulting elevator deflection, and the time gap between elevator deflection and affected altitude change. This observation, however, requires further exploration because introducing a 500 ms additional transport delay does not make any visible impact on the correlation graphs of a flight.

The correlation between elevator deflection and time derivative of altitude becomes zero at the same time gap when the correlation between elevator deflection and altitude has a local maximum or minimum value. An examination of the aileron-heading and the rudder-heading correlations suggest that similarities or lack of similarities between the two kinds of correlations correspond to the presence or absence of coordinated use of aileron and rudder by the pilot. Additional work is recommended to investigate cross correlations between pilot input and airplane response to search for their characteristic features which would determine different progressive stages of pilot training on simulators. The UNIX based simulation system that has been installed and used for the present work is suitable for a future study of the Pilot Induced Oscillations. The installation of rudder pedals suitable for the UNIX based simulator system is strongly recommended as an improvement in the system.

NOMENCLATURE

| <u>Symbol</u> | <u>Description</u> | <u>Units</u> |
|-----------------|--------------------------------------------------------------------------------------|--------------|
| ms | Milliseconds. | milliseconds |
| rms | Root mean square. | _____ |
| t | Time. | instant |
| τ | Time gap. | seconds |
| τ_m | Time gap for the maximum absolute value of negative correlation. | seconds |
| H (t) | Instantaneous value of airplane altitude. | feet |
| avg H | Time average value of altitude for a 3 minute flight. | feet |
| h (t) | H (t) - avg H, fluctuating part of altitude. | feet |
| h' | rms value of h. | _____ |
| h_{i+j} | h at the (i + j) time interval of a flight, each interval is 0.025 ms. | feet |
| Ψ | Heading, zero indicates Northward direction. | _____ |
| ψ (t) | ψ (t) - avg ψ , fluctuating part of heading. | _____ |
| Δ | Elevator deflection, positive for upward deflection. | _____ |
| avg Δ | Time average Δ for a 3 minute flight. | _____ |
| δ_i | δ at the i^{th} time interval of a flight, each interval = 0.025 ms. | _____ |
| δ' | rms value of δ . | _____ |
| δ (t) | Δ (t) - avg Δ , fluctuating part of elevator deflection. | _____ |
| δ_a (t) | Fluctuating part of aileron deflection. | _____ |
| δ_r (t) | Fluctuating part of rudder deflection. | _____ |
| CORR (τ) | Coefficient of cross correlation between two signals with time gap τ . | _____ |
| DEP | Stick deflection for elevator or deflection of elevator, according to context. | _____ |
| DAP | Stick deflection for aileron or deflection of aileron, according to context. | _____ |
| DRP | Pedal movement for rudder or deflection of rudder, according to context. | _____ |
| HDOT | Time derivative of H. | ft. / sec. |
| PSI | Heading, zero indicates Northward direction. | degree |
| SEL | Single-Engine Land (aircraft type). | _____ |
| MEL | Multi-Engine Land (aircraft type). | _____ |
| INST | Instrument Rating (FAA-certification). | _____ |
| AIAA | American Institute of Aeronautics and Astronautics. | _____ |
| NASA | National Aeronautics and Space Administration. | _____ |
| PIO | Pilot Induced Oscillation. | _____ |
| CPU | Central Processing Unit. | _____ |
| SGI | Silicon Graphics, Inc. | _____ |

REFERENCES

1. McRuer, D. T. and Graham, D. (1981), "*Eighty Years of Flight Control: Triumphs and Pitfalls of the Systems Approach*," Journal of Guidance, Control, and Dynamics, Vol. 4, No.: 4, pages 353 - 362.
2. Ashkenaz, I. L. (1984), "*Twenty Years of Handling Qualities Research*," Journal of Aircraft, Vol. 21, No.: 5, pages 289 - 301.
3. Washizu, K., and Miyajima, K., (1963), "*Controllability Limit of Human Pilot*," AIAA Journal, Vol. 3, No.: 5, Pages 941 - 947.
4. Smith, R. H., (1963), "*Comment on Controllability Limit of Human Pilot*," AIAA Journal, Vol. 3, No.: 10, Pages 1980 - 1981.
5. Smith, R. H., (1977), "*Theory for Longitudinal Short Period Pilot Induced Oscillations*," Air Force Flight Dynamics Lab, Wright Patterson AFB, OH, AFFDL-TR-77-57.
6. Bjorkman, E. A., 1986, "*Flight Test Evaluation of Techniques to Predict Longitudinal Pilot Induced Oscillations*," Air Force Institute of Technology, Wright Patterson AFB, OH, AFIT/GAE/AA/86J-1, December 1986.
7. Hess, R. A., and Kalteis, R. M., 1991, "*Techniques for Predicting Longitudinal Pilot Induced Oscillations*," Journal of Guidance, Control, and Dynamics, Vol. 14, pages 198 to 204.
8. Cardullo, F. M., and George, G., 1993, "*Transport Delay Compensations: An Inexpensive Alternative to Increasing Image Generator Update Rate*," AIAA Paper No. 93-3563-CP.
9. Middendorf, M.S., and McMillan, G. R., 1991, "*The Effect of Simulator Transport Delay on Performance, Workload, and Transport Activity During Low Level Flight*," AIAA Paper No. 91-2965-CP.
10. Williams, J. P., and Johnson, Y. A., 1997, "*Pilot Input and Airplane Response Cross Correlations on a Flight Simulator With and Without Transport Delay*." Presented at the AIAA Southeastern Regional Student Conference, Atlanta, GA. (A copy of the paper is included in Appendix B).

11. Norlin, Ken A., 1995, "*Flight Simulation Software at NASA Dryden Flight Research Center*," AIAA Paper No. 95-3419.
12. Roskam, J., 1995, "*Airplane Flight Dynamics and Automatic Flight Controls*," Parts I&II, DAR Corporation, Lawrence, KS.
13. Goto, N., and Matsuo, T., 1988, "*Identification of Pilot Dynamics in a System with a Choice of Feedback Structures*," Journal of Guidance, Control, and Dynamics, Vol. 11, No. 2, pages 159-166.
14. Etkin, B. and Reid, L. D., 1996, "*Dynamics of Flight Stability and Control*," Wiley, New York.

APPENDIX A

The graphs of the raw data for the five selected flights of pilots P3 and P4. These flights are discussed in the main text.

B represents the pilot's best flight without additional transport delay.

BD represents the pilot's best flight with additional transport delay.

AD represents the pilot's average flight with additional delay.

The x-axis in all the graphs shows time from 0 to 180 seconds. The control input signals and the airplane response signals are plotted on the y-axis.

H = airplane altitude (ft.).

HDOT = dh/dt (ft./sec.).

PSI = airplane heading (radians in this appendix, degrees in the main text).

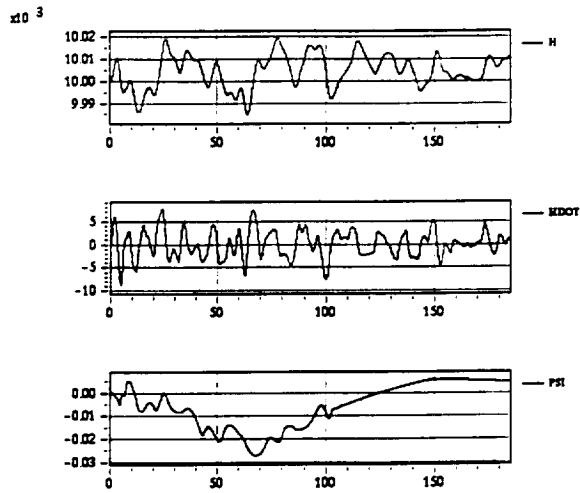
DEP represents joystick movement (in.) to deflect the elevator.

DAP represents joystick movement (in.) to deflect the ailerons.

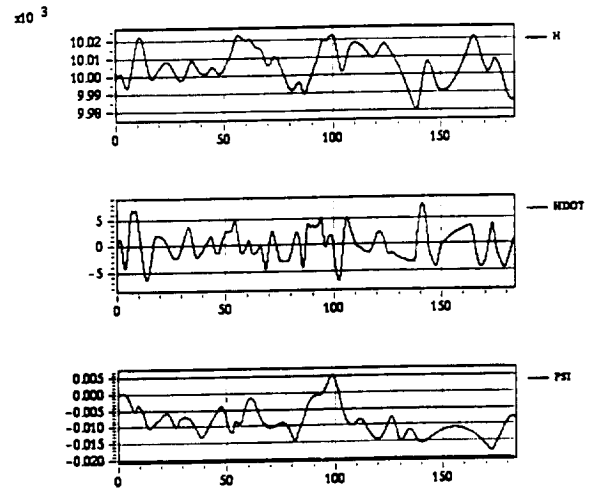
DRP represents rudder pedal movement (in.) to deflect the rudder.

On a proportional scale, DEP, DAP, and DRP may also be interpreted as the deflections of elevator, ailerons, and rudder, respectively.

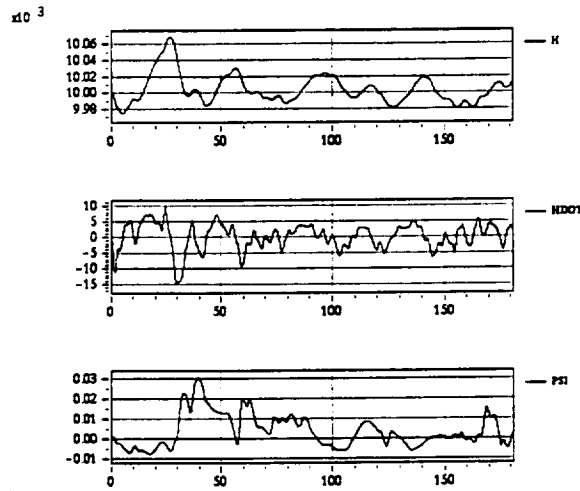
P3_B.dat



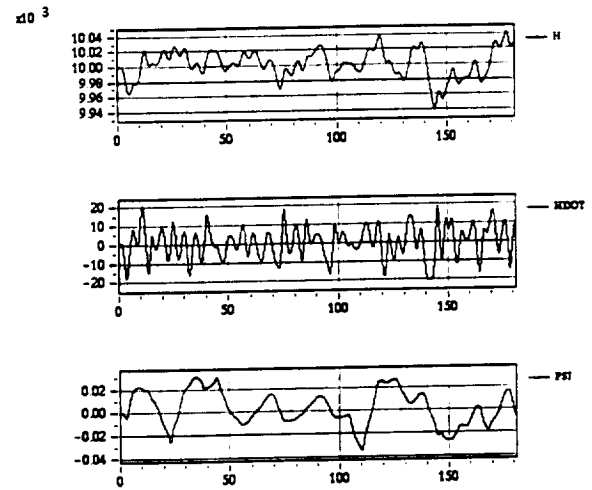
P4_B.dat



P3_BD.dat



P4_BD.dat



P3_AD.dat

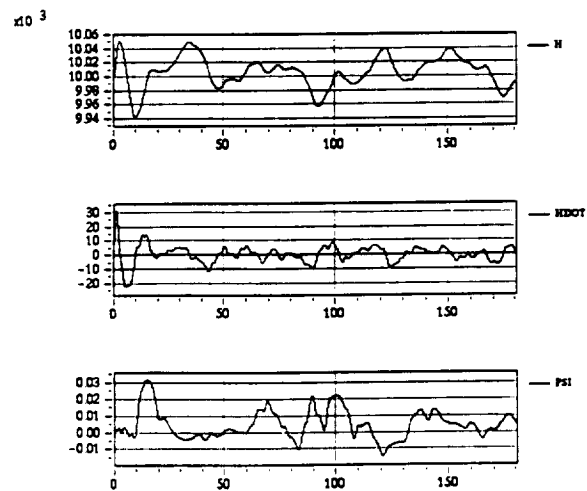
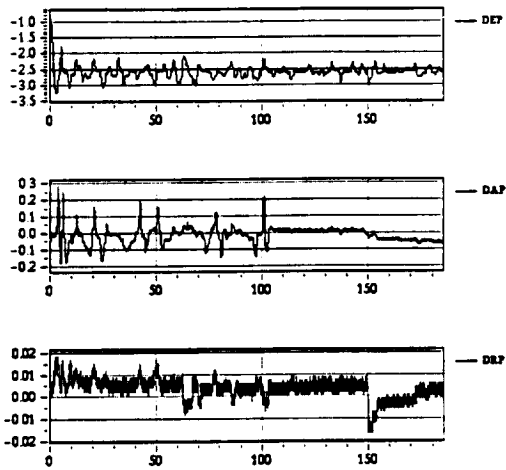
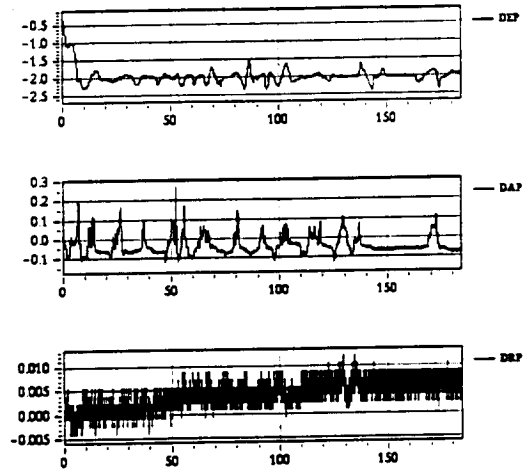


Figure A1: Airplane altitude, time derivative of altitude, and airplane heading vs. time for the five selected flights. For nomenclature, please see the first page of Appendix A.

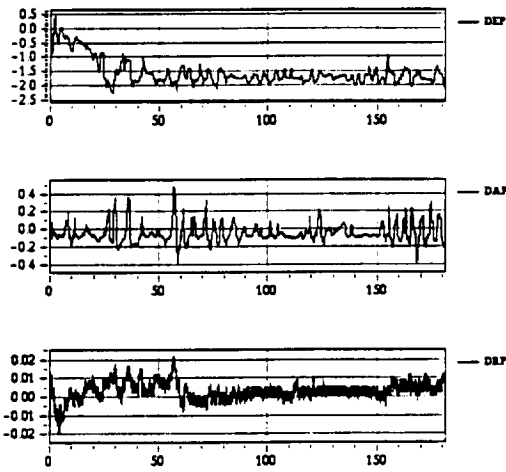
P3_B.dat



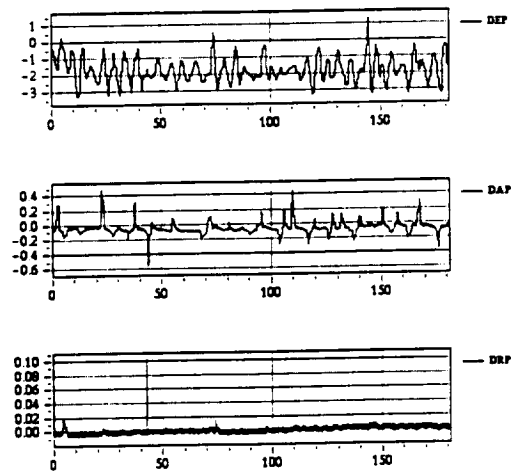
P4_B.dat



P3_BD.dat



P4_BD.dat



P3_AD.dat

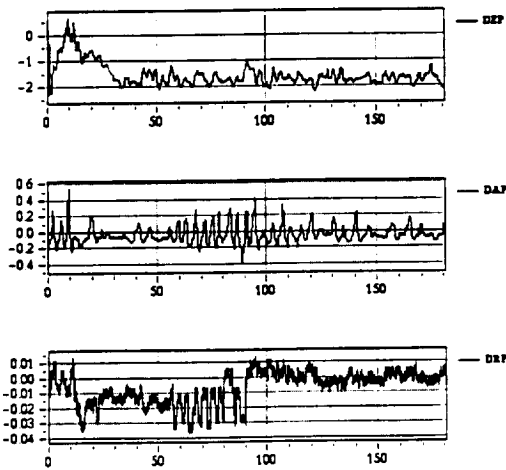


Figure A2: Pilot inputs to move the elevator, aileron, and rudder, respectively vs. time for the five selected flights. For nomenclature, please see the first page of Appendix A.

APPENDIX B

Copy of the paper "*Pilot Input and Airplane Response Cross Correlations on a Flight Simulator With and Without Transport Delay.*" The paper was presented by Jason Paul Williams and Yusef Ali Johnson at the AIAA Southeastern Regional Student Conference, held on April 10 and 11, 1997 in Atlanta, GA. The work reported here was performed as part of the present project under the NASA Dryden grant number NAG 2 - 4006.

**PILOT INPUT AND AIRPLANE RESPONSE
CROSS CORRELATIONS ON A FLIGHT SIMULATOR
WITH AND WITHOUT TRANSPORT DELAY**

Jason Paul Williams

Undergraduate Senior

Yusef Ali Johnson

Undergraduate Senior

Aerospace Science Engineering Department

Tuskegee University

Tuskegee, AL 36088

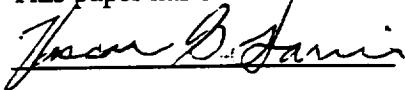
Presented to:

The AIAA Southeastern Regional Student Conference

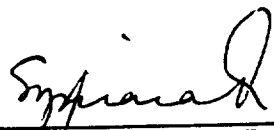
April 10, 11 1997

Atlanta, GA

This paper has been reviewed and approved for presentation by:

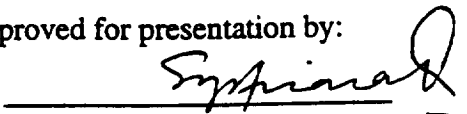


Dr. Vascar Godfrey Harris, Professor



Dr. Syed Firasat Ali, Associate Professor

This paper has been reviewed and approved for presentation by:



Dr. Syed F. Ali

AIAA Faculty Advisor

Abstract

Four volunteer pilots were required to maintain given altitude and heading on a computer based stationary flight simulator of the F-15E fighter airplane. One set of flights was obtained without any additional delay between the stick input and the appearance of airplane response. In another set of flights, a 500 ms additional delay was used. The deviations in altitude and heading and the fluctuations in the altitude indicated that the flights with 500 ms delay were appreciably deteriorated. This is in agreement with the other recent investigations. The cross-correlations between elevator deflection and altitude reveal interesting aspects of pilot's performance. In particular, these correlations reveal that different pilots exercised a variety of techniques for maintaining straight level flights. The C++ source code, which is used for the computation of the desired correlations, is also included.

Introduction

For human operators in a feedback control system, their ability to adapt to variations in control tasks is generally acknowledged as a significant advantage. Baron¹ says, "With training and proper feedback, pilots are capable of adapting their control strategies to a wide range of task variables." Baron, however, reminds us that this adaptive capacity is not unlimited. The transport delay or a delay between input signals and their response is one of the most important factors that needs studies for different flight situations to understand whether they fall within the pilot's adaptive capacity. The papers published by Cardullo et al², Lusk et al³, and Middendorf et al⁴ are some of the recent studies on the effect of simulator transport delay on pilot's performance and on the ways of compensating delays. The present paper offers a study of the airplane responses to stick inputs with and without an additional transport delay. Four volunteer pilots conducted straight level flights on an F-15E flight simulator. The pilots used the joy stick to maintain a given altitude and a given heading. Two sets of flights were conducted. In one set the standard simulator was used and in the other a 500 ms additional delay was programmed between the stick input and the appearance of airplane response on the monitor. The deflections of elevator and ailerons were treated as pilot's inputs, and the altitude and heading of the airplane were treated as the responses. In the present study the average and rms values of the elevator deflection and altitude signals as well as the cross correlations between these two signals are presented as the statistical tools to compare pilot's performances. A C++ code to compute the desired cross-correlations from the flight data is provided in the appendix. The present paper is included in the final report on a flight simulation research project at Tuskegee University sponsored by NASA Dryden Flight Simulation Research Center under the Grant NAG2-4006, June 1994 to January 1997.

Background

The simulation software, which represents the dynamics of flight of an F-15E fighter, has been installed by NASA Dryden Flight Research Center on an SGI 4D/420 IRIS workstation. On the IRIS alone, the simulator could be operated by a mouse. To operate the simulator by a joystick, its graphic software has been moved to an SGI INDIGO 2 workstation. The two workstations are connected through ethernet. Thus the F-15E simulation software used in the present study operates on three central processing units, two on an SGI IRIS workstation and one on an SGI INDIGO 2 workstation. The pilot in the loop operation is comprised of the simulation software, the pilot, and

a BG System joystick called a FlyBox. Norlin⁵ has provided a description of the software design, model development, and simulation capabilities of the system together with a description of other NASA Dryden Systems. The F-15E simulation is coded with a FORTRAN shell and C support routines and operates on a UNIX - based platform. The integration scheme in the simulation has been optimized for real time operation. The code has the flexibility to program a desired transport delay between the stick input and the airplane response on the monitor. In a simulated flight, the digital data on forty-two different flight parameters can be recorded at every 25 ms time interval. The flight parameters include the altitude, heading, and velocity, as well as the deflections of elevator, rudder, and ailerons. Provisions for turbulence and gust, although available, were not used for this study.

Experimental Protocol

Four volunteer pilots conducted the required flights for the experimental study on the F-15E airplane real time simulation. Three of the them were experienced licensed pilots and one of them had no prior experience of flying. In this paper, the volunteer pilots are named as P1, P2, P3, and P4. The ages, flying hours, and license status of the pilots are P1: 69 yrs, 3200 hrs, SEL, MEL, INST; P2: 48 yrs, 100 hrs, SEL, MEL, INST; P3: 23 yrs, 830 hrs, SEL, MEL, INST; and P4: 26 yrs, no flying experience.

In every test flight a pilot was required to maintain straight level flight for three minutes duration heading toward North, with pre-adjusted throttle for flying at 450 knots indicated at 10,000 ft. altitude with autotrim off. During the flight, the pilot inputs to the joystick were limited to elevator and aileron deflections only. A measure of performance, named rsws score, was calculated for a flight from its altitude and heading data. An rsws score is the square root of the sum of the weighted squares of maximum deviations in heading and altitude. Let Δh in ft. be the maximum absolute deviation from the required 10,000 ft. altitude. Let $\Delta\Psi$ in degrees be the maximum absolute deviation from the required Northward heading. Then

$$\text{rsws} = \text{sqrt} [(\Delta\Psi)^2 + (\Delta h/10)^2] \quad (1)$$

It is obvious that a smaller value of the rsws score represents superior pilot performance. Two kinds of test flights were conducted. One kind of flight simulated a normal flight without inserting additional delay between stick inputs and the appearance of airplane response on the computer monitor. The second kind of flight had a 500 ms transport delay programmed between the stick inputs and airplane response. For each of the two kinds of flights, a pilot was

trained and evaluated by conducting several three minute flights and by calculating the respective rsws scores. An asymptote in performance consisted of six consecutive flights of the same kind in which the pilot did not break his own rsws score record. The flights of each kind that represented the asymptote in performance for every pilot formed the data base for further analysis. In addition to the rsws scores, other criteria were also considered to compare different flights. For the present paper, attention is focused on the elevator deflection, Δ as input signal and altitude of airplane, H as the response or output signal. The time average values of Δ and H are $\text{avg } \Delta$ and $\text{avg } H$. The fluctuating parts of the two signals are $\delta(t) = \Delta(t) - \text{avg } \Delta$ and $h(t) = H(t) - \text{avg } H$, where t represents time. The rms value of δ and h are denoted by δ' and h' . The cross-correlation between δ and h for arbitrary time gap τ is denoted as $\text{CORR}(\tau)$ and defined as:

$$\text{CORR}(\tau) = \frac{1}{T \delta' h'} \int_{t=0}^{t=T} \delta(t) h(t + \tau) dt \quad (2)$$

The simulator provides data at every 25 ms interval, thus a 3 minute flight has 7201 data points for each signal.

The cross-correlation is therefore calculated as follows:

$$\text{CORR}(j) = \frac{1}{(7200 - j) \delta' h'} \sum_{i=1}^{(7201-j)} \delta_i^* h_{i+j} \quad (3)$$

To cover a time gap, τ , of 20 seconds for correlation, $\text{CORR}(j)$ is calculated for $j = 1, 2, \dots, 7201$. For each kind of flight for every pilot, the correlation graphs, $\text{CORR}(\tau)$ vs τ are obtained for only three flights amongst the six flights that determine the asymptote in performance; these three flights are the best, the worst, and the average based on the rsws scores. An initial estimate of 20 second maximum time gap, τ , was considered sufficient for correlation. Upon considerable computations we learned that longer time gaps would have been desirable.

Flight Data Analysis

In Table I, P1, P2, P3, and P4 are the four volunteer pilots who conducted two kinds of straight level flights of three minutes duration. The column 1 for each flight has rsws scores. A lower value of rsws indicates better pilot's performance. The columns 2 and 3 have rms values of elevator deflection in degrees and altitude fluctuations in ft.,

respectively; their lower values also indicate better pilot's performance. From Table I it is apparent that 500 ms transport delay has caused deteriorated pilot's performance. Middendorf et al⁴ has noted that 300 ms delay resulted in significant deterioration of pilot's performance. Lusk et al³ have conducted an elaborate study on the delay compensation. With 300 ms delay they observed more significant deterioration in heading performance than in the altitude performance. Consideration of pilot P2 in Table I brings up an interesting aspect of pilot's strategy. Unlike other pilot's, the pilot P2 has smaller rms value of elevator deflection for the flight with transport delay than the flight with no transport delay. To obtain improved understanding of pilot's performance, cross-correlations are obtained between the elevator deflection and altitude. From amongst the flights that represented asymptotic performance of a pilot, only the best, the worst, and the average, are processed to report the cross-correlations. Thus for the two kinds of flights by every pilot, a total of twenty-four cross-correlation curves are reported. Figures 1, 2, 3, and 4 show the cross-correlations between the fluctuating parts of elevator deflection, $\delta(t)$ and the altitude $h(t + \tau)$ for the time gap, τ ranging between 0 and 20 seconds. The positive value of δ represents upward deflection of the elevator that gives decrease in lift on the tail and which should result in nose up tendency of the airplane. Thus the positive δ is expected to result in positive h . Twenty-three out of twenty-four correlation graphs show negative correlations for the time gap values near zero. While conducting their test flights, the pilots had observed that in the event of leaving the stick free, the airplane had a tendency to climb up. To arrest the climb up tendency, the pilot moves the elevator down that gives rise to negative correlation. Thus the negative values in the first part of the correlation curves reveal lack of trim. Let τ_m be the time gap at which the negative correlation has the maximum absolute value. The τ_m is ranging between zero and 600 ms and it does not seem affected by the transport delay. We would expect τ_m to provide a measure of the pilot's reaction time delay but its apparently unpredictable variations do not meet the expectations. It may be noted here that Roskam⁶ assumes 100 ms reaction time for test pilots and 120 to 200 ms for other pilots. For larger time gaps, most correlation curves show appreciable positive values. It is suspected that they are caused by the Phugoid oscillation of the airplane, reinforcing the desire to extend time gap delays to larger values.

References

1. Baron, Sheldon, "Pilot Control." Human Factors in Aviation, Academic Press Inc., 1988, pages 347-385.
2. Cardullo, Frank M., and G. George, "Transport Delay Compensations: An Inexpensive Alternative to Increasing Image Generator Update Rate," AIAA Paper No. 93-3563-CP, 1993.
3. Lusk, Steven L., C. D. Martin, and J.D. Whiteley, "Time Delay Compensation Using Peripheral Visual Cues in An Aircraft Simulator," AIAA Paper No. 90-3129-CP, 1990.
4. Middendorf, Mathew S., and G. R. McMillan, "The Effect of Simulator Transport Delay on Performance, Workload, and Control Activity During Low Level Flight," AIAA Paper No. 91-2965-CP, 1991.
5. Norlin, Ken A., "Flight Simulation Software at NASA Dryden Flight Research Center," AIAA Paper No. 95-3419, 1995.
6. Roskam, Jan, Airplane Flight Dynamics and Automatic Flight Controls, DAR Corporation, Lawrence, Kansas, 1995, page 765.

Conclusion

For all pilots observed in the study during straight level flight on a simulator, the additional transport delay of 500 ms, between the stick input and appearance of airplane response on the monitor, results in appreciable deterioration of the flight. This is in agreement with the other recent studies which indicate deterioration in flight with 300 ms transport delay. The cross-correlations between elevator deflection and altitude signals support a belief that in a non-perturbed flight, different pilots exercise a variety of techniques for maintaining straight level flight. It is proposed that cross-correlations between the elevator deflections and aileron deflections shall provide an improved understanding of pilot's technique on a flight.

Acknowledgments

This work is part of a research project on "A Low Cost Simulation System to Demonstrate Pilot Induced Oscillations," sponsored by NASA Dryden Flight Research Center under grant number NAG2-4006. We wish to thank Dr. Syed Firasat Ali, PI on the project, for providing us with the opportunity to participate in flight simulation research and for his guidance and encouragement. From NASA Dryden, Larry Schilling's support and encouragement, and Ken Norlin's expert help on the simulation software remained vital for maintaining the progress. Thanks are due to Dennis Ezell, whose contributions to the project have been significant in initiating flight simulation research at Tuskegee University and in motivating fellow aerospace engineering students to engage in this research. We are thankful to Dr. Amnon Katz from the University of Alabama and Dr. Vascar G. Harris from Tuskegee University, who are both pilots and aerospace engineering professors, and who remained available for valuable guidance and contributions. The advisement on software issues received from Dr. C.L. Chen, Abraham George and Ernest Kashiri is sincerely appreciated.

Nomenclature

| <u>Symbol</u> | <u>Description</u> | <u>Units</u> |
|----------------|-----------------------------------------------------------------------------------------------|--------------|
| t | Time | instant |
| τ | Time gap | seconds |
| τ_m | Time gap for the maximum absolute value of negative correlation | seconds |
| Δ | Elevator deflection, positive for upward deflection. | degree |
| avg Δ | Time average of heading for a 3 minute flight. | degree |
| δ | δ at the time interval of a flight, each interval is 0.025 ms. | milliseconds |
| δ' | rms value of δ . | ----- |
| $\delta(t)$ | $\Delta(t) - \text{avg } \Delta$, fluctuating part of heading. | degree |
| h_{i+j} | at $(i + j)$ the time interval of a flight, each interval is 0.025 ms. | milliseconds |
| h' | rms value of h . | ----- |
| $h(t)$ | $H(t) - \text{avg } H$, fluctuating part of altitude. | feet |
| H | Flight altitude. | feet |
| ΔH | Maximum absolute deviation in altitude, from 10,000 ft. | feet |
| avg H | Time average value of altitude for a 3 minute flight, ft. | feet |
| Ψ | Heading, zero for Northward heading. | degree |
| $\Delta \Psi$ | Maximum absolute deviation in heading, from zero deg. | degree |
| rsws | Square root of the sum of the weighted squares of maximum deviations in heading and altitude. | ----- |
| CORR(τ) | Coefficient of cross-correlation $\delta(t)$ and $h(t + \tau)$. | ----- |
| SEL | Single-engine Land (aircraft type) | ----- |
| MEL | Multi-engine land (aircraft type) | ----- |
| INST | Instrument Rating (FAA certification) | ----- |

| Pilot | Flight Without Transport Delay | | | Flight With Transport Delay of 500 ms | | |
|-------|--------------------------------|------|------|---------------------------------------|------|------|
| | 1 | 2 | 3 | 1 | 2 | 3 |
| P1 | 26.4 | 0.60 | 73.8 | 52.2 | 1.02 | 77.1 |
| P2 | 29.3 | 0.51 | 51.2 | 33.5 | 0.20 | 66.4 |
| P3 | 3.2 | 0.23 | 7.5 | 5.8 | 0.45 | 18.2 |
| P4 | 3.7 | 0.25 | 9.4 | 6.3 | 0.72 | 18.7 |

Table I: Comparison of Pilot's Performance in Flights With and Without Transport Delay.

1 - Average rsws for the best 5 flights, 2 - δ' deg in the best flight, 3 - h' ft in the best flight.

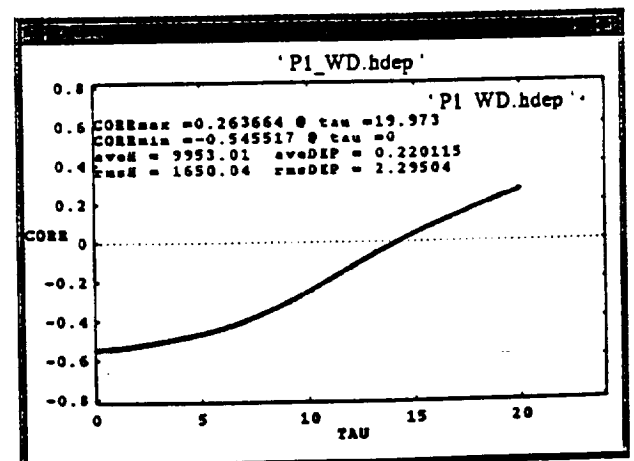
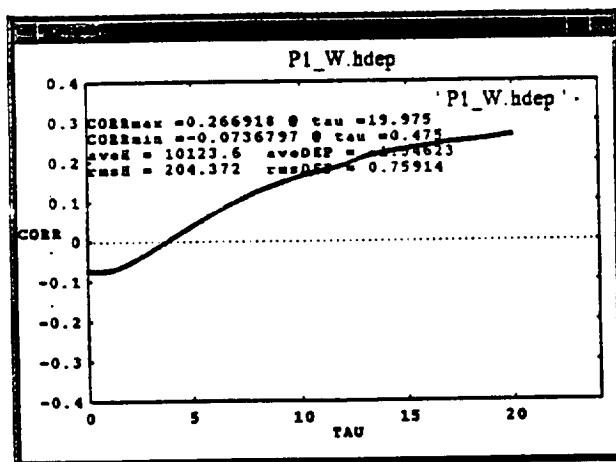
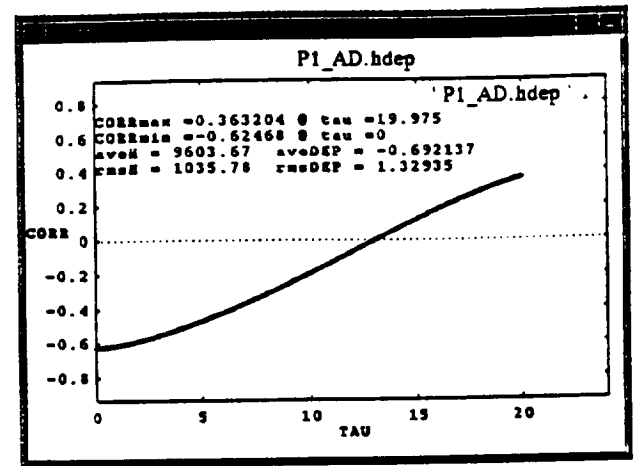
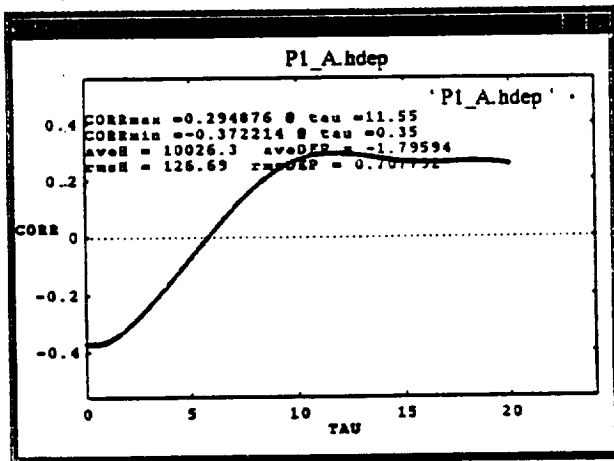
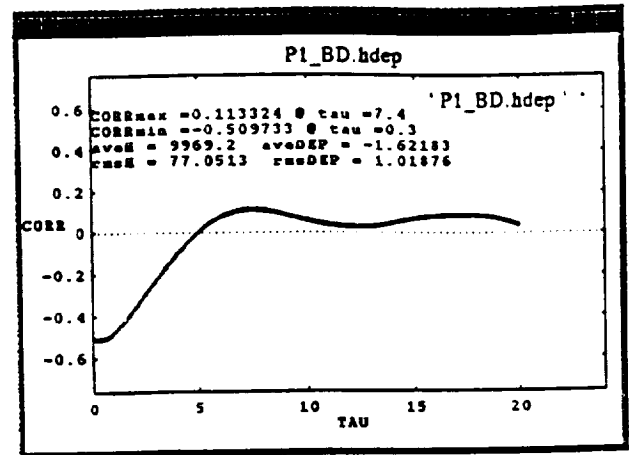
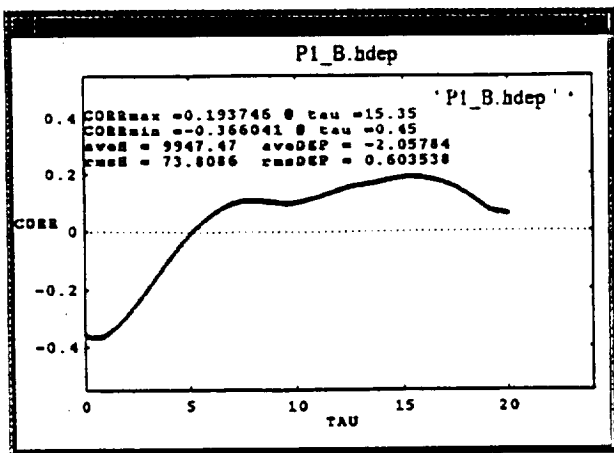


Figure 1: Cross-Correlations Between Elevator Deflection and Altitude of the Airplane for Pilot P1

B, A, and W are the pilot's best, average, and worst flights without additional transport delay

BD, AD, and WD are the pilot's best, average, and worst flights with additional transport delay of 500 ms.

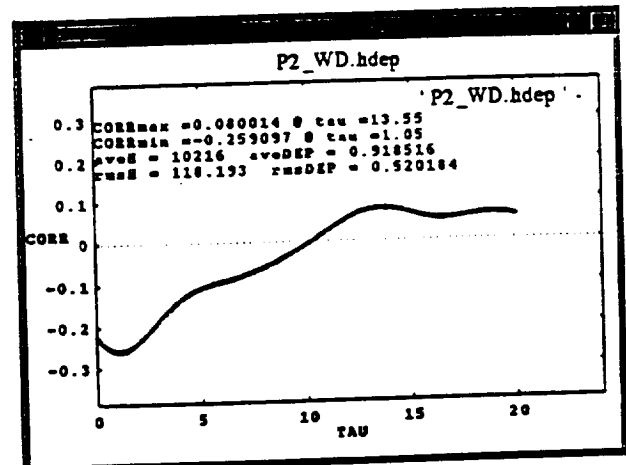
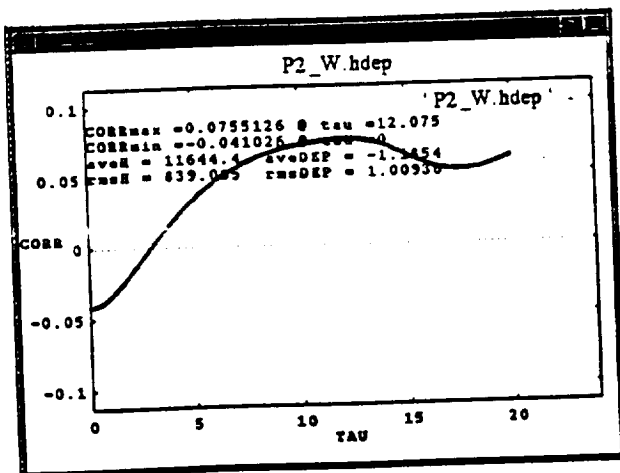
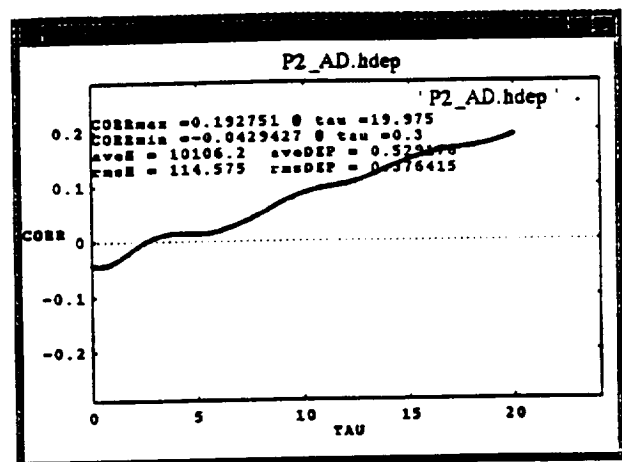
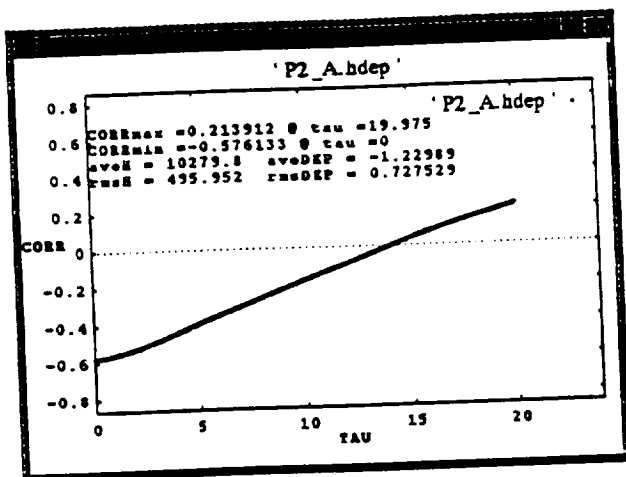
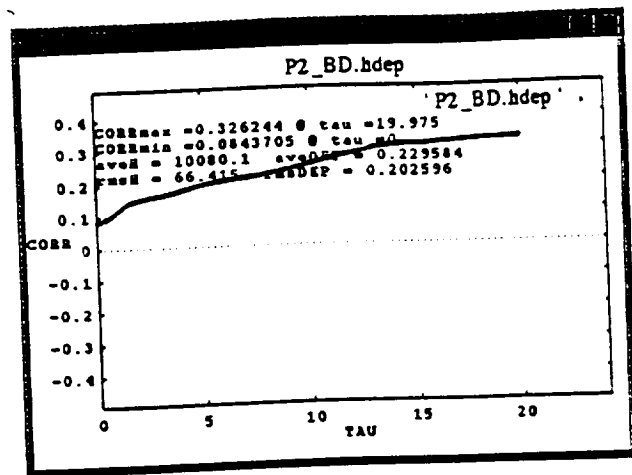
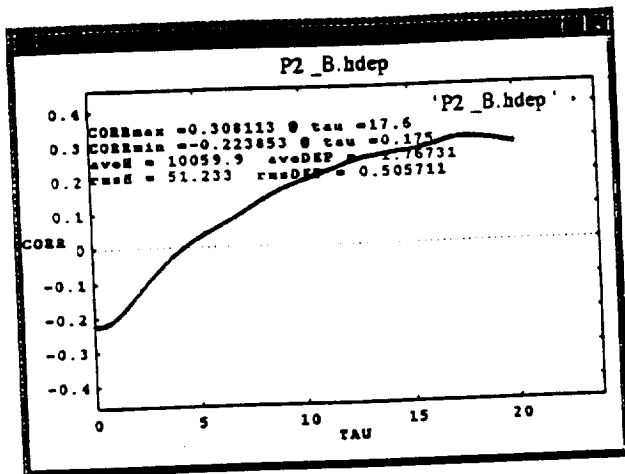


Figure 2: Cross-Correlations Between Elevator Deflection and Altitude of the Airplane for Pilot P2
 B, A, and W are the pilot's best, average, and worst flights without additional transport delay
 BD, AD, and WD are the pilot's best, average, and worst flights with additional transport delay of 500 ms.

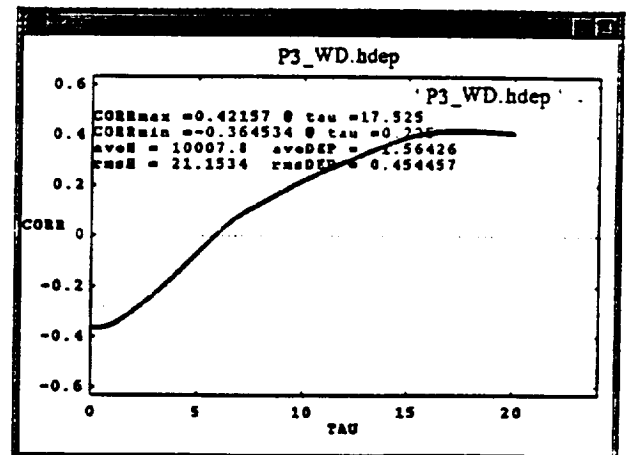
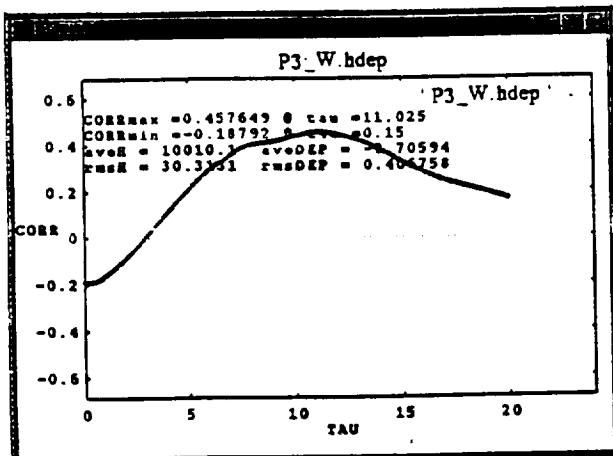
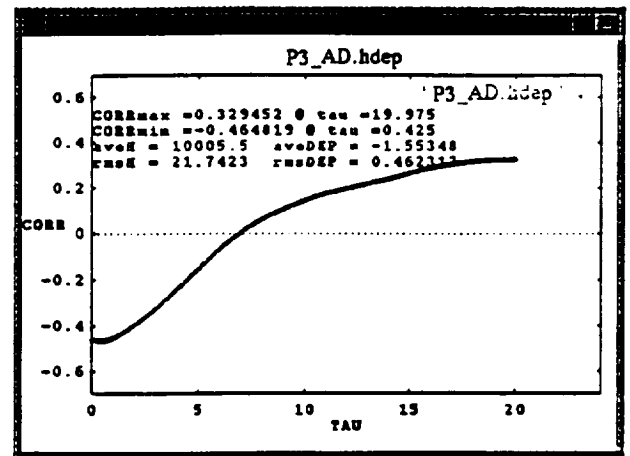
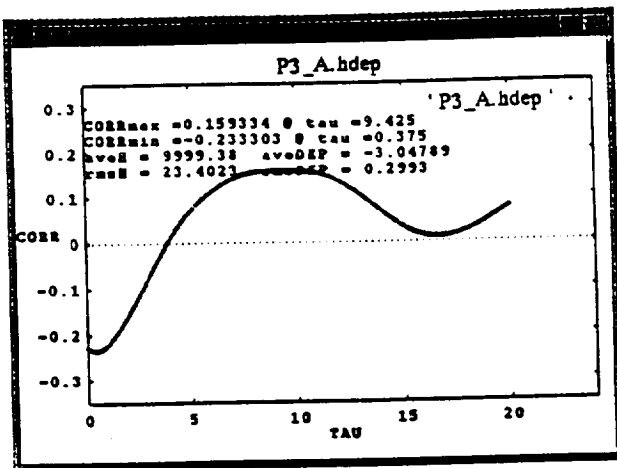
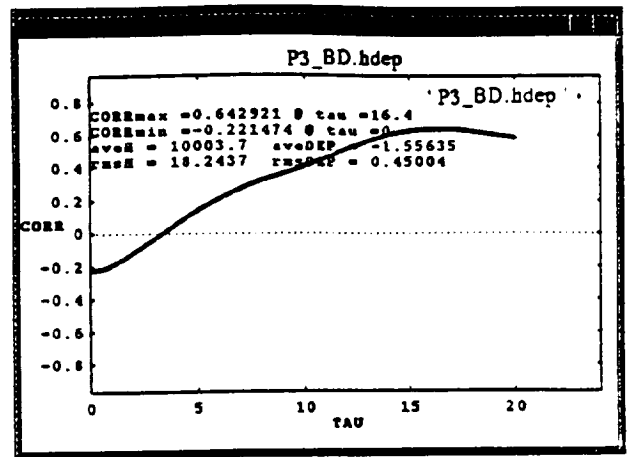
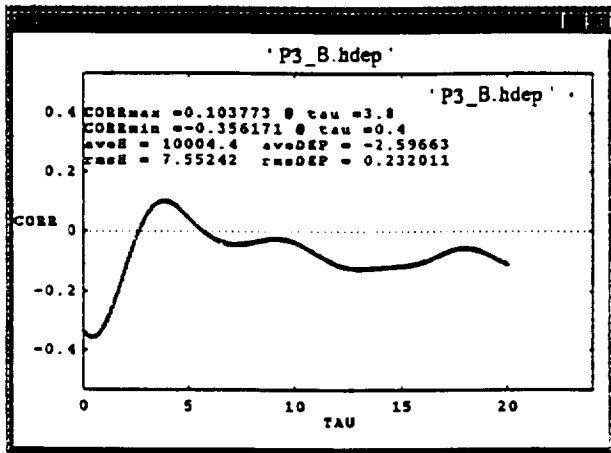


Figure 3: Cross-Correlations Between Elevator Deflection and Altitude of the Airplane for Pilot P3

B, A, and W are the pilot's best, average, and worst flights without additional transport delay

BD, AD, and WD are the pilot's best, average, and worst flights with additional transport delay of 500 ms.

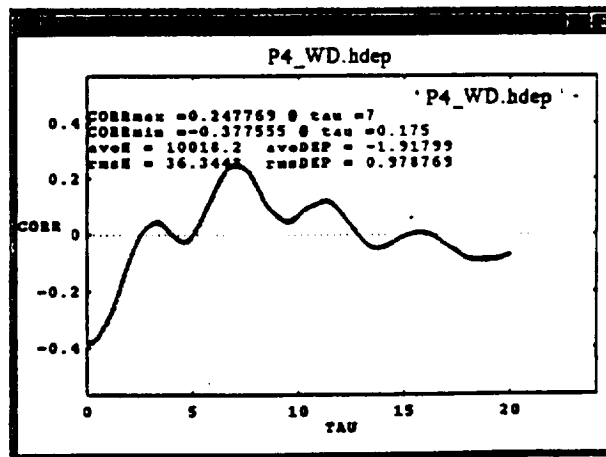
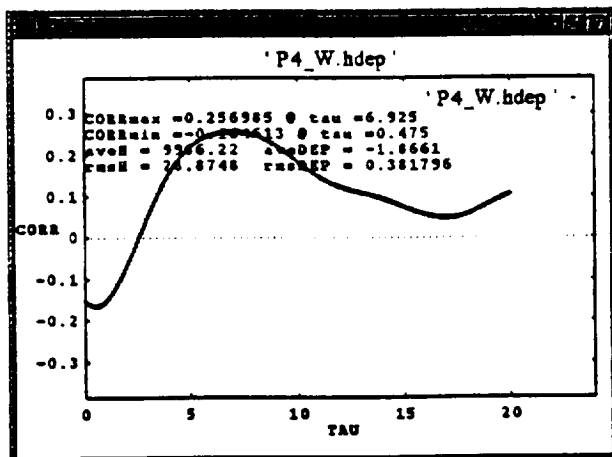
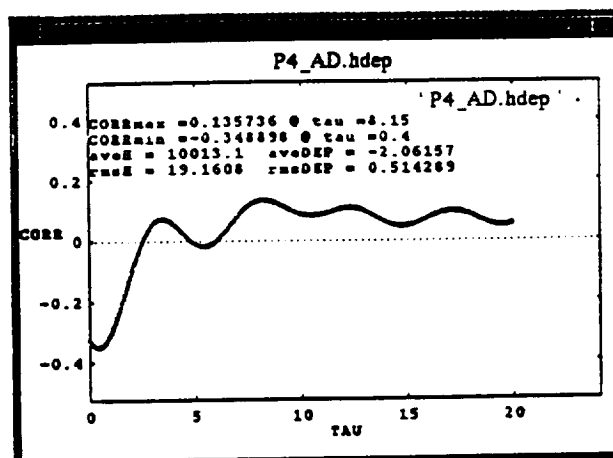
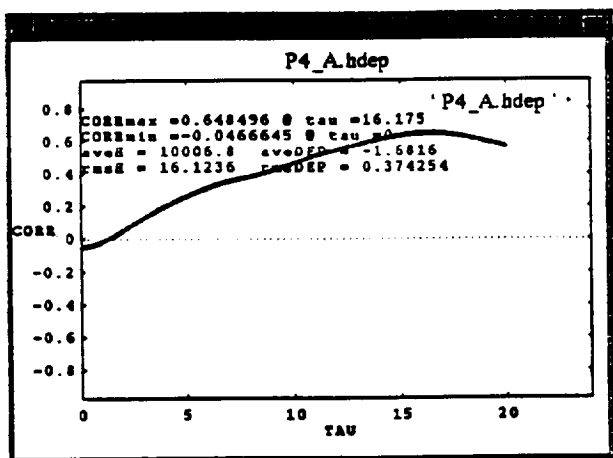
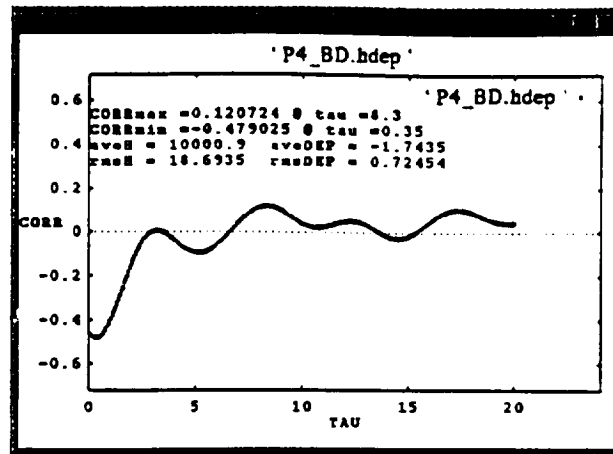
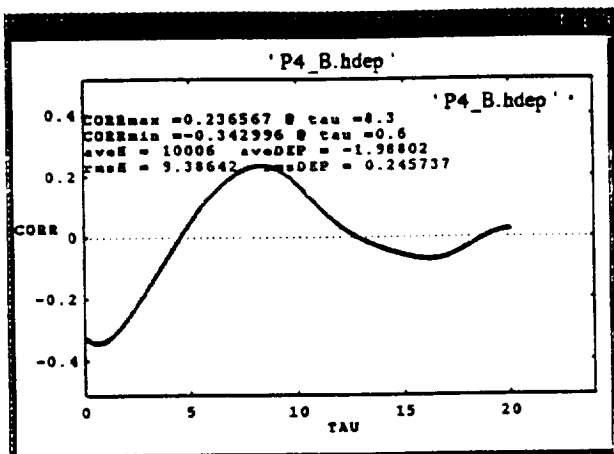


Figure 4: Cross-Correlations Between Elevator Deflection and Altitude of the Airplane for Pilot P4

B, A, and W are the pilot's best, average, and worst flights without additional transport delay

BD, AD, and WD are the pilot's best, average, and worst flights with additional transport delay of 500 ms.

Appendix

The complete program written in C++ is enclosed. The program reads the F-15E simulation data after the data file has been converted from binary to ASCII. The program was compiled on IRIX 5.3 C/C++ compiler 4.0.2 on the SGI Indigo2 workstation. Pages 15 to 17 contain the Correlation Source Code. Pages 18 and 19 have the Correlation Header. Page 20 has the Script Source Code. The program prints out the calculated correlation values and the jargon for plotting the graphs on a GNU Plot Program. The Script file separates the jargon from the data, and it creates a script file for the GNU Plot Program.

```

#include <fstream.h>
#include <string.h>
#include <math.h>
#include "corr1.hpp"          /* correlation header */
#define L 7200                /* maximum number of points */

void main()
{
    char fileName[80];         /* input filename */
    char FileNme[80];          /* output filename */
    char buffer[80];           /* buffer */
    char text[255];            /* notes character variable */
    char CA[10];               /* name of A(t + tau) */
    char CB[10];               /* name of B(t) */
    char FileData[80];
    char FileLoad[80];

    int chan;                  /* number of channels */
    int i, ii = 0, j = 0, k = 0;
    int n[10];                 /* data pointer */
    int w;                     /* correlation type */
    int cf;                     /* maximum correlation factor */
    int point;                 /* enter maximum number of point */
    double U;
    double d;                  /* tau value at maximum correlation */
    double e;                  /* tau value at minimum correlation */
    double Numb;               /* data buffer */
    double yu;                 /* maximum correlation */
    double yl;                 /* minimum correlation */
    double xmin;               /* minimum x value of graph */
    double ymin;               /* minimum y value of graph */
    double xmax;               /* maximum x value of graph */
    double ymax;               /* maximum y value of graph */

    CORR DATA, Scorr, corr;
    rename:

    cout << " Filename: ";
    cin >> fileName;           /* filename of the ascii */
    cout << " Enter the maximum correlation factor ";
    cin >> cf;                  /* enter maximum correlation factor */
    cout << " Enter number of points ";
    cin >> point;              /* enter maximum number of point */
    cout << " Please choose and correlation (H_DEP=1, PSI_DAP=2, PSI_DRP=3): ";
    cin >> w;                  /* correlation selection */

    /* opens the data file. if not file exist then the file name is asked
       for again */
    ifstream fin(fileName.c_str(), ios::nocreate);
    if (!fin)
    {
        cout << " Unable to open :: " << fileName << " *** file not found *** \n\n";
        cout << " Please re-enter the filename. \n\n";
        goto rename;
    }
    cout << " \n Filename " << fileName << " was found. \n";

    /* reads unneeded jargon left by the getData program */
    for (i = 0; i < 5; i++)
    {
        fin >> buffer;
    }

    fin >> chan;               /* reads the number of channels */
    cout << "\n This file has " << chan << " channels. \n";

    /* reads and sorts the number of channels */

```

```

for ( i= 0; i < (chan+2); i++ )
{
    fin >> buffer;
    if (!(strcmp(buffer,"T"))) { n[0] = j;}
    if (!(strcmp(buffer,"H"))) { n[1] = j;}
    if (!(strcmp(buffer,"PSI"))){ n[2] = j;}
    if (!(strcmp(buffer,"DAP"))){ n[3] = j;}
    if (!(strcmp(buffer,"DEP"))){ n[4] = j;}
    if (!(strcmp(buffer,"DRP"))){ n[5] = j;}
    j++;
}

/* reads and sorts the data to thier correct arrays */
while ((fin >> Numb) && (k < (point)) )
{
    if ( ii == n[0] ) { DATA.T[k] = Numb; }
    if ( ii == n[1] ) { DATA.H[k] = Numb; }
    if ( ii == n[2] ) { DATA.PSI[k] = Numb; }
    if ( ii == n[3] ) { DATA.DAP[k] = Numb; }
    if ( ii == n[4] ) { DATA.DEP[k] = Numb; }
    if ( ii == n[5] ) { DATA.DRP[k] = Numb; }
    ii++;
    if (ii== (chan+1)) {ii = 0; k++;}
}

fin.close(); /* closes the input file */

/* sets values initialize to the corrolation header*/
DATA.cf=cf;
DATA.www;
DATA.k=k;
DATA.corr();

/* finds the maxium upper and lower points of the corrolation */
yl = DATA.CORPA[0];d=0;yu = DATA.CORPA[0];e=0;
for ( i = 0; i < cf; i++ )
{
    if(yl > (DATA.CORPA[i])){yl = (DATA.CORPA[i]);d=i*(.025);}
}
for ( i = 1; i < cf; i++ )
{
    if(yu < (DATA.CORPA[i])){yu = (DATA.CORPA[i]);e=i*(.025);}
}
if(fabs(yu) < fabs(yl)){U=yl;} cout <<U;
if(fabs(yu) > fabs(yl)){U=yu;} cout <<U;
xmax = ((DATA.TAU[cf-1])*0.2+DATA.TAU[cf-1]);
xmin = 0;
ymin = -(fabs(U+U*.50));
ymax = (fabs( U+U*.50));

Rename:
cout << " Filename: ";
cin >> FileName; /* name of the output file */
cout << " Enter one line of comments for data file :\n";
cin.ignore(1, '\n'); /* enter notes on the graph */
cin.getline(text,255);

/* sorts the the file name */
strcpy (FileData.FileName);
strcpy (FileLoad.FileName);
strcat (FileLoad,".gif");
if (ww=1)
{
    strcat (FileData,".hdep");
    strcat (CA,"H");
    strcat (CB,"DEP");
}

```

```

    }
    if (w==2)
    {
        strcat (FileData, ".pdap");
        strcat (CA, "PSI");
        strcat (CB, "DAP");
    }
    if (w==3)
    {
        strcat (FileData, ".pdrp");
        strcat (CA, "PSI");
        strcat (CB, "DRP");
    }
    if (w==4)
    {
        strcat (FileData, ".edrp");
        strcat (CA, "DEP");
        strcat (CB, "DRP");
    }
    if (w==5)
    {
        strcat (FileData, ".edap");
        strcat (CA, "DEP");
        strcat (CB, "DAP");
    }
}

/* opens output file */
ofstream fout(FileData, ios::noreplace);
if (!fout)
{
    cout << " Unable to create and write to " << FileName << " *** file already,
    cout << " Please re-enter the filename. \n\n";
    goto Rename;
}

/* writes script jargen */
fout << "% set title \"<<FileData<<\"'\n";
fout << "% set xlabel \"TAU\"'\n";
fout << "% set ylabel \"CORR\" 0,-10\"'\n";
fout << "% set label 1 \"CORRmax = <<yu<< \" tau = <<e<<\"' at << xmin*.9 <<\",
fout << "% set label 2 \"CORRmin = <<yl<< \" tau = <<d<<\"' at << xmin*.9 <<\",
fout << "% set label 3 \"ave<<CA<<\" = <<DATA.aveA<<\" ave<<CB<<\" = <<DATA.at
fout << "% set label 4 \"rms<<CA<<\" = <<DATA.rmsA<<\" rms<<CB<<\" = <<DATA.rz
fout << "% plot (x=<< xmin <<\":<< xmax:
fout <<\" [\"<< ymin <<\":<<ymax<<\"] \"<<FileData<<\"'\n";
fout <<\" tau[i] corr[i] \" << \"\n";
fout <<\" \" << fileName << \"\n";
fout <<\" \" << text << \"\n";
fout <<\" tau[i] corrH[i] \" << \"\n";

/* writes results to output file */
for ( i = 0; i < cf; i++)
{
    fout << DATA.TAU[i] <<\"t\" << DATA.CORPA[i] << \"\n";
}

fout.close(); /* closes output file */
cout << \"\nFilename \"<< FileData << \" was created. \n\";
cout << \"\nNow run script and use \"<<FileData<<\" script file.\n\";
}

```



```

#include <math.h>
#include <fstream.h>

#define L 7200

class CORR
{
public:

    int i, j, k;
    int w;
    int cf;
    int z;
    double T[1], H[1], PSI[1], DAP[1], DEP[1], DRP[1], TAN[1], CORPA[1];
    double t, h, psi, dap, dep, drp;

    double aveA, aveB;
    double sqdA, sqdB;
    double mnsqA, mnsqB;
    double rmsA, rmsB;
    double corp, corn;
    double sma, smb;
    double smsqA, smsqB;
    double smcorn, smcorp;
    double A[1];
    double B[1];
    double difB[1];
    double difA[1];
    double corpa;
    double corna;
    double tau;

    CORR(){}
    ~CORR(){}
    void Scorr ()
    {
        T[z]=t, H[z]=h, PSI[z]=psi, DAP[z]=dap, DEP[z]=dep, DRP[z]=drp;
    }
    void corr ()
    {
        /* sets all sum variables to zero
        places then correct signals to be correlated to A and B
        and sums A and B */
        sma = 0, smb = 0, smsqA = 0, smsqB = 0, smcorn = 0, smcorp = 0;
        if (w==1)
        {
            for ( i = 0; i < k; i++ )
            {
                A[i] = H[i]; B[i] = DEP[i];
                sma = sma + A[i];
                smb = smb + B[i];
            }
        }
        if (w==2)
        {
            for ( i = 0; i < k; i++ )
            {
                A[i] = PSI[i]; B[i] = DRP[i];
                sma = sma + A[i];
                smb = smb + B[i];
            }
        }
        if (w==3)
        {

```

```

    for ( i = 0; i < k; i++ )
    {
        A[i] = PSI[i]; B[i] = DAP[i];
        sma = sma + A[i];
        smb = smb + B[i];
    }
}
if (w==4)
{
    for ( i = 0; i < k; i++ )
    {
        A[i] = DRP[i]; B[i] = DEP[i];
        sma = sma + A[i];
        smb = smb + B[i];
    }
}
if (w==5)
{
    for ( i = 0; i < k; i++ )
    {
        A[i] = DAP[i]; B[i] = DEP[i];
        sma = sma + A[i];
        smb = smb + B[i];
    }
}
aveA = sma/(k); /* average of A */
aveB = smb/(k); /* average of B */
for (i = 0; i < k; i++)
{
    difB[i] = (B[i] - aveB); /* difference between B[i] and aveB */
    difA[i] = (A[i] - aveA); /* difference between A[i] and aveA */
    sqdB = pow(difB[i], 2.0);
    sqdA = pow(difA[i], 2.0);
    smsqA = smsqA + sqdA;
    smsqB = smsqB + sqdB;
}
mnsqA = smsqA/(k);
mnsqB = smsqB/(k);
rmsB = (sqrt(mnsqB)); /* rms value of B */
rmsA = (sqrt(mnsqA)); /* rms value of A */
for (j = 0; j < cf; j++)
{
    for (i = 0; i < (k-j+1); i++)
    {
        corp = difB[i] * difA[i+j];
        smcorp = smcorp + corp;
    }
    tau = j * 0.025;
    corpa = smcorp/((k - j) * rmsB * rmsA); /* correlation coefficient */
    smcorp = 0;
    TAU[j] = tau;
    CORPA[j] = corpa; /* correlation coefficient array */
}
};

```

```

#include <fstream.h>
#include <string.h>
void main()
{
    char fileName[80], buffer[255], WRITE[255]=' ', fileLoad[80], str1[80];
    int i,n;
    // enter filename
    cout << " Filename: ";
    cin >> fileName;
    cout << " \n Filename " << fileName << " was found. \n" ;
    ifstream fin(fileName.ios::nocreate);
    str1[1] = '\0';
    n = 0;
    while (fileName[n] != '.')
    {
        str1[0] = fileName[n];
        strcat(fileLoad, str1); n++;
    }
    strcat(fileLoad, ".gif");
    cout << " \n Filename " << fileLoad << " was created. \n\n" ;
    cout << " Now run gnuplot and load \"<< fileLoad << "\" \n";
    ofstream fout(fileLoad.ios::noreplace);
    for (i=0; i<8; i++)
    {
        fin.get(buffer, 2); fin.getline(WRITE, 255);
        fout << WRITE << "\n";
    }
}

```